To my family--Without their love and support none of this would have been possible.
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ESSAYS ON INTERNATIONAL TRADE, GROWTH AND THE ENVIRONMENT

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The relationship between environmental degradation and economic growth has been central to the debate over sustainable growth. The first chapter uses utility growth as an index of sustainable growth, which is positively related to economic growth and negatively related to environmental degradation. Skilled and unskilled labor are used in this economy and the population is growing over time generating growth without scale effects. The pollution growth rate is higher in a decentralized economy, whereas the sustainable growth rate is higher in an economy with a social planner. An increased rate of population growth is associated with a higher sustainable growth rate in both economies. A higher share of skilled labor is associated with a higher sustainable growth rate in a decentralized economy.

A simple monopolistic competition model is developed to examine the impact of environmental standards upon firms' profitability, pollution and consumers' welfare. There is a continuum of firms and each firm produces a variety with different environmental quality. The second chapter shows that when regulators impose a more stringent environmental standard, there will be fewer firms in the market at the steady-state equilibrium; firms' average profits will be higher as competition will be less intense;
and the overall effect on the welfare of consumers will be ambiguous because the effect on pollution generated is unclear. In addition, an optimal standard is calculated under Pareto distribution and the factors which affect the optimal standard are discussed.

The third chapter develops a trade model to examine the impact of trade liberalization upon firms' profitability, pollution and consumers' welfare. Firms with high levels of environmental quality export, whereas firms with low levels of environmental quality only serve the domestic market. An increase in the number of trading partners raises the cutoff export environmental quality; a reduction in foreign market entry costs reduces the cutoff export environmental quality; and a reduction in per-unit trade costs reduces the cutoff export environmental quality. A more stringent environmental standard increases successful firms' revenues and profits. Due to trade liberalization, firms that only serve the domestic market make lower revenues and profits; firms that are able to export will increase their sales to foreign countries, compensating for their loss from domestic sales and making overall revenues higher. Trade liberalization ultimately increases aggregate consumption.
CHAPTER 1
IS POPULATION BAD FOR THE ENVIRONMENT

Introduction

Can the pursuit of economic growth cause the world to come to an end? Are we paying too much attention to productivity, while ignoring the damage to our natural resources? Alternatively, can economic growth be the driving force behind improvements in our environmental quality and standards of living? The relationship between environmental degradation and economic growth has been central to the debate over sustainable growth.

This paper builds upon Byrne’s (1997) three-sector endogenous growth model where technology is the engine of growth and pollution could be abated. It compares optimal solutions in a decentralized economy (equilibrium) with an economy with a social planner (first-best). Using utility growth as an index of sustainable growth, it captures the interaction between economic growth and environmental degradation. Similar to the outcome demonstrated by Byrne, optimal pollution control reduces the pollution growth rate without necessarily lessening economic growth. However, Byrne’s paper suffers a scale-effects problem. The rate of technological progress is assumed to be proportional to the level of Research and Development (R&D) inputs. For example, if R&D inputs are doubled, the growth rate of technological progress also will double. This scale-related characteristic implies that an economy’s long-run per-capita growth rate increases in proportion to the population. In the presence of positive population growth,

\footnote{The most commonly used definition of sustainable development is given in the Brundtland Report (1987), it defines sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs.}
the scale-effects characteristic implies that the per-capita growth rate increases exponentially over time, becoming infinite in steady-state equilibrium.²

The model presented in this paper assumes that labor is the only factor of production in the economy and that population is growing at a positive rate. This paper has important policy implications. By introducing exogenous population growth, it asks whether sustainable growth is possible with a growing population. Further, it shows the need for the government to put effort into pollution abatement activities and to set limits on economic growth to ensure a sustainable growth rate. Since skilled labor and unskilled labor are distinguished, this paper also sheds some light on the impact of education and skilled labor migration on the sustainable growth path.

The impact of population growth on sustainable growth has been debated intensely. Pessimists believe that a growing population is one of the greatest threats to the environment and the natural resource base. In “An essay on the principal of population,” Malthus (1798) expresses concerns about a possible tendency of human populations to grow more rapidly than can be accommodated by arable land and other components of the resource base. This tendency would sow the seeds of human self-decline. Malthus further suggested that increases in fertility would tend to offset the underlying output increase. Brander (2007) suggests that continued demographic transition to lower fertility is the primary requirement for achieving sustainable growth. High population growth rates can dissipate the surplus that might otherwise support investment in R&D. Optimists, such as Boserup (1981) and Simon (1981), propose the induced innovation hypothesis that population growth itself induces more rapid

² See Jones (1995a, 1995b) for further discussion of scale-effects property.
technological pressures. As population increases, more pressure is placed on the existing agricultural system, stimulating invention. Kremer (1993) additionally suggested that very long-run time series evidence (from “1 Million B.C. to 1990”) was consistent with this induced innovation hypothesis. Barbier (1998) develops an endogenous growth model with resource scarcity and population growth to explore balanced growth properties. Barbier assumes that resource availability constrains the supply of innovation, and concluded that it is still possible to achieve a long-run growth of per capita consumption while avoiding resource exhaustion. Pender (1998) employs a neoclassical growth model, using capital and natural capital as inputs to production. He found that population growth had a positive impact on investment in renewable resources and other forms of capital and a negative impact on per capita production and consumption (based on the assumption of constant or decreasing returns to scale production function). This chapter argues that higher population growth could lead to a higher sustainable growth rate under certain conditions. When the population grows at a higher rate, benefits from innovation are greater (creating economic incentives to innovate) and sustainable growth may be achieved.

The Model

Overview

The standard optimal control techniques are used to solve the utility maximization problems of a representative infinitely lived consumer and compare the market equilibrium growth path with the efficient growth path. Labor is the only factor in this economy which is growing at an exogenous rate $n$ and is partitioned into two distinct
types: skilled labor which is denoted by $H(t)$ and unskilled labor which is denoted by $L(t)$.

Labor can be employed in three activities (sectors): manufacturing which uses both skilled and unskilled workers, produces goods for consumption and generates pollution emissions during the production process; R&D which uses only skilled labor is pollution neutral; and pollution abatement which uses both skilled and unskilled labor reduces pollution emissions. Both skilled labor and unskilled labor are assumed to be perfectly and costlessly mobile across sectors.

**Consumers and Workers**

I model consumers as dynastic households with infinitely lived members. In this economy, there is a fixed unit length measure of identical households who provide labor services.

Each individual member of a household lives forever and is endowed with either one unit of skilled labor or one unit of unskilled labor, which is supplied inelastically to the labor market. The size of each household, measured by the number of its members, grows exponentially at a fixed positive rate $n$ which is the population growth rate. Normalizing the initial size of each household to unity assuming each household is endowed with $S$ share of skilled labor and $1-S$ share of unskilled labor, the number of household members at time $t$ is given by $e^{nt}$. Assume $\bar{H}$ and $\bar{L}$ are the initial number of skilled and unskilled labor in this economy, let $H(t) = \bar{H}e^{nt}$ denote the supply of skilled
labor at time \( t \), \( L(t) = \bar{L}e^{nt} \) denote the supply of unskilled labor and \\
\( N(t) = \bar{N}e^{nt} = H(t) + L(t) \) denote the aggregate supply of labor\(^3\).

Therefore, at any time \( t \), both the skilled labor share \((S)\) and the unskilled labor share \((1-S)\) are constant in each household and in the whole economy, depending on their initial endowment shares respectively:

\[
S = \frac{H(t)}{N(t)} = \frac{\bar{H}e^{nt}}{\bar{N}e^{nt}} = \frac{\bar{H}}{\bar{N}} \quad (1-1)
\]

and,

\[
1 - S = \frac{L(t)}{N(t)} = \frac{\bar{L}e^{nt}}{\bar{N}e^{nt}} = \frac{\bar{L}}{\bar{N}} \quad (1-2)
\]

Denote skilled labor in manufacturing, R&D and pollution abatement as \( H_M, H_A \) and \( H_Z \) respectively. Further, denote unskilled labor in manufacturing and pollution abatement as \( L_M \) and \( L_Z \). Then the full employment conditions are given as

\[
H = H_M + H_A + H_Z \quad \text{and} \quad L = L_M + L_Z.
\]

Divide both sides of these two equations by the total population \( N(t) \), we can get \( \frac{H}{N} = \frac{H_M}{N} + \frac{H_A}{N} + \frac{H_Z}{N} \) and \( \frac{L}{N} = \frac{L_M}{N} + \frac{L_Z}{N} \). Thus, the full employment conditions can be rewritten as:

\[
S = h_M + h_A + h_Z \quad (1-3)
\]

and,

\[
1 - S = l_M + l_Z. \quad (1-4)
\]

where the lower case \( h \) and \( l \) denote the per capita skilled and unskilled labor.

\(^3\) I have assumed that both skilled and unskilled labors are growing at the same rates as the total population simply because the model does not have steady state equilibrium if the growth rates differ.
Manufacturing

Firms in the manufacturing sector hire skilled labor $H_M$ and unskilled labor $L_M$ to produce a single final good $Y(t)$. All output is consumed at each point in time:

$$Y(t) = C(t) = A(t)H_M^aL_M^{1-a}$$  \hspace{1cm} (1-5)

where $C(t)$ is the instantaneous consumption and $A(t)$ is the level of technology at time $t$. Per capita consumption expenditure $c(t)$ can be expressed as:

$$c(t) = \frac{C(t)}{N(t)} = \frac{Y(t)}{N(t)} = \frac{A(t)H_M^aL_M^{1-a}}{N(t)} = A(t)h_M^aI_M^{1-a},$$  \hspace{1cm} (1-6)

where $h_M$ and $l_M$ are the per capita skilled and unskilled labor respectively. As Byrne (1997) states, “this structure has no technological spillovers, and thus, highlights the effect of the pollution externality. Without an environmental externality, the competitive equilibrium will be optimal growth. Any divergences between the efficient and equilibrium paths are therefore due to the environmental externality.”

Total Factor Productivity

As in equation (1-5), technology is one of the inputs of production. In the R&D sector, only skilled labor can be used to discover new technology and innovate. There is no depreciation of technology and R&D is pollution neutral, which means, in the innovation process, skilled labor does not generate any pollution. The evolution of total factor productivity is governed by the following knowledge production function:

$$g_A = \frac{\dot{A}(t)}{A(t)} = \frac{H_A(t)}{X(t)},$$  \hspace{1cm} (1-7)

where $g_A$ denotes the growth rate of technology, $H_A(t)$ is skilled labor devoted to R&D activities and $X(t)$ is a measure of R&D difficulty. Higher value of $X(t)$ implies that the
same number of skilled workers generates a lower growth rate of technology\(^4\).

Assumptions that govern the evolution of \(X(t)\) play a crucial role in regulating the scale-effects property and in conditioning the nature of long-run Schumpeterian growth.

Following the variety-expansion approach\(^5\), I assume that aggregate R&D difficulty is directly proportional to the number of varieties and the production of \(X(t)\) does not require any economic resources. Under the right market structure assumptions (profit-maximization and market-driven free entry of monopolistically competitive firms), it can be shown that the number of varieties is directly proportional to the level of the economy’s population\(^6\):

\[
X(t) = \beta N(t),
\]

(1-8)

where \(\beta\) is an inconsequential parameter.

Substituting equation (1-8) into equation (1-7) yields:

\[
g_A = \frac{A(t)^*}{A(t)} = \frac{H_A(t)}{X(t)} = \frac{H_A(t)}{\beta N(t)} = \frac{h_A}{\beta},
\]

(1-9)

where \(h_A\) is per-capita skilled labor devoted to R&D activities.

**Pollution Abatement**

The presence or absence of the pollution abatement sector is the key to whether we can lower pollution, support ongoing growth and provide reasonable predictions for

---

\(^4\) Segerstrom (1998) was the first study to introduce variable \(X(t)\) in the knowledge production function of a scale-invariant Schumpeterian growth model based on quality improvements.

\(^5\) Peretto (1998) introduced the variety-expansion approach where vertical product differentiation takes the form of process innovations. Young (1998) also introduced the variety-expansion approach where vertical product differentiation is modeled as quality improvements. Aghion and Howitt (1998, Chapter 12), Dinopoulos and Thompson (1998) and Howitt (1999) have developed further this approach.

\(^6\) This linear relationship between the number of varieties and the level of population can be derived from market-based mechanisms with solid micro foundations. See Dinopoulos and Sener (2007) for more details.
the costs of pollution control. Following Byrne (1997), I assume that pollution stock \( Z(t) \) is growing at a rate \( g_z \) which takes the following form:

\[
g_z = \frac{Z(t)}{Z(t)} = \phi_1 h_M + \phi_2 l_M - \gamma h_Z l_Z^{1-\sigma}.
\]  

(1-10)

According to equation (1-10), emissions are the byproduct of the manufacturing process and are directly caused by per capita skilled labor \( h_M \) and unskilled labor \( l_M \) devoted to production. I assume that the growth rate of the pollution stock rises linearly in per-capita skilled and unskilled labor in manufacturing and is not affected by the current level of technology. Parameters \( \phi_1 \) and \( \phi_2 \) measure the dirtiness of the production process in manufacturing and can be thought of as pollution intensities. Higher values of parameters \( \phi_1 \) and \( \phi_2 \) are associated with higher rates of pollution for any given amount of per capita skilled and unskilled labor. In addition, if \( \phi_1 \) is greater (lower) than \( \phi_2 \), then additional skilled (unskilled) labor is more polluting.

The last term of equation (1-10) represents the pollution abatement technology. The presence of an explicit pollution abatement sector allows for greater flexibility in the tradeoffs between production and environmental degradation. Emission abatement activities also depend on per-capita skilled labor \( h_Z \) and unskilled labor \( l_Z \) with the precise dependence captured by a Cobb-Douglas function. Parameter \( \gamma \) measures the effectiveness of the abatement process and can be thought of as a fixed level of abatement technology.\(^7\)

---

\(^7\) For future research, an abatement R&D sector can be included to relax this fixed abatement technology.
Sustainable Growth

The intertemporal utility of a representative household is defined as

\[ U = \int_0^\infty e^{-(\rho-n)t} \ln v(t) \, dt, \quad (1-11) \]

where \( \rho \) is the subjective discount rate. The greater \( \rho \) is, the less the consumer values future consumption relative to current consumption. \( n \) is the population growth rate. \( \rho - n \) is the effective discount rate, which must be greater than zero. \( v(t) \) is the instantaneous utility function which depends on per-capita consumption expenditure \( c(t) \) and on the pollution stock \( Z(t) \) at time \( t \):

\[ v(t) = c(t)Z(t)^{-\varepsilon}, \quad (1-12) \]

where parameter \( \varepsilon \) represents the relative utility of consumption and pollution.\(^8\) The sustainable growth rate is defined as the long-run rate of growth of per capita instantaneous utility, which takes into account the growth rates of both consumption and the pollution stock:

\[ g_u = \frac{\dot{v}}{v} = \frac{\dot{c}(t)}{c(t)} - \varepsilon \frac{\dot{Z}(t)}{Z(t)}. \quad (1-13) \]

The sustainable growth rate is affected positively by growth in consumption and negatively by growth in pollution emissions. There is a tradeoff between economic growth and pollution abatement since limited resources have to be allocated between them.

---

\(^8\) Parameter \( \varepsilon \) will likely be different among countries and captures different preferences for a clean environment in a society. Developed countries tend to care more about the environment they are living in, i.e., \( \varepsilon \) is higher; Developing countries worry more about their economic growth, so they will put less emphasis on pollution, i.e., \( \varepsilon \) is lower.
The Decentralized Economy

Since pollution is modeled as a negative externality, households will take the aggregate pollution stock as given, denoted by \( Z(t) \), and households have no incentive to put their efforts into emission reduction activities. Thus, in the absence of government intervention, no pollution abatement is undertaken, \( H_Z = L_Z = 0 \). Emissions are unabated; the growth of pollution stock only depends on the per-capita skilled labor devoted to the manufacturing sector and the aggregate per-capita unskilled labor, thus the growth rate of pollution emissions is always positive:

\[
g_Z = \frac{Z(t)}{Z(t)} = \phi_1 h_M + \phi_2 l_M. \tag{1-14}
\]

Each household maximizes the following lifetime utility:

\[
U = \int_0^\infty e^{-(n-\nu)t}[\ln c(t) - \varepsilon \ln Z(t)]dt, \tag{1-15}
\]

subject to the following constraints:

\[
c(t) = A(t) h_M \alpha l_M^{1-\alpha}, \tag{1-16}
\]

\[
A(t) = A(t) \dot{h}_M / \beta, \tag{1-17}
\]

\[
S = h_M + h_A, \tag{1-18}
\]

and,

\[
1 - S = l_m. \tag{1-19}
\]

In this decentralized economy, skilled labor is divided between manufacturing and technology improvement, while unskilled labor is used only in the manufacturing sector.
At the steady state equilibrium, the allocation of per capita skilled labor in the manufacturing sector, $h_M^0$, and the R&D sector, $h_A^0$, the growth rate of technology, $g_A^0$, the growth rate of pollution stock, $g_Z^0$, and the sustainable growth rate of this economy, $g_u^0$, are all constant and given by (derivation shown in Algebraic Details):

\[ h_M^0 = \alpha \beta (\rho - n), \quad (1-20) \]

\[ h_A^0 = S - \alpha \beta (\rho - n), \quad (1-21) \]

\[ g_A^0 = \frac{S}{\beta} - \alpha (\rho - n), \quad (1-22) \]

\[ g_Z^0 = \alpha \beta \phi_1 (\rho - n) + \phi_2 (1 - S), \quad (1-23) \]

and,

\[ g_u^0 = \frac{S}{\beta} - \alpha (\rho - n) - \varepsilon \alpha \beta \phi_1 (\rho - n) - \varepsilon \phi_2 (1 - S). \quad (1-24) \]

If the share of skilled labor in the population $S$ is less than $\alpha \beta (\rho - n)$, all the skilled labor will be devoted to the manufacturing sector, no technology improvement is undertaken, $h_A^0 = 0$, and there is no economic growth in this decentralized economy.

Since all individuals take pollution as given and do not abate emissions, the growth rate of pollution emissions is always positive and the sustainable growth rate is always negative. Equation (1-24) leads to the following proposition which establishes the existence of long-run sustainable growth.

\textbf{Proposition 1-1:} In a decentralized economy the long-run sustainable growth rate is positive if and only if:

\[ S > \frac{\alpha \beta (\rho - n)(1 + \varepsilon \beta \phi_1) + \varepsilon \beta \phi_2}{1 + \varepsilon \beta \phi_2}. \quad (1-25) \]
Condition (1-25) holds for a sufficiently high amount of skilled labor. Therefore, if a decentralized economy has a large skilled labor share $S$, the disutility from the increasing pollution is outweighed by the gains to technology accumulation. This allows for a positive sustainable long-run growth rate. However, if the skilled labor share $S$ is not large enough, there will either be no technology accumulation or the positive utility from technology accumulation will be dominated by the disutility from the increasing pollution. In this case, the sustainable growth rate is negative.

**Proposition 1-2:** If condition (1-25) holds, then a decentralized economy with a higher rate of population growth experiences a higher rate of technological progress, a lower growth rate of pollution and a higher sustainable growth rate.

The intuition behind proposition 1-2 is as follows: in this decentralized economy, both skilled and unskilled labor are growing at the same rate as population growth, therefore the shares of skilled and unskilled labor must always be constant. If population is growing at a higher rate, all unskilled labor will still work in the manufacturing sector. However, skilled labor will move to the R&D sector from the manufacturing sector, leading to a higher technology growth rate. The growth rate of pollution depends on the shares of skilled and unskilled labor in manufacturing. Since higher population growth reduces the share of skilled labor in manufacturing without affecting the share of unskilled labor in manufacturing, the growth rate of pollution decreases. Higher technology growth and lower pollution growth lead to higher long-run sustainable growth. Thus, contrary to popular beliefs, population growth is good for the environment.
Proposition 1-3: In the decentralized economy, a higher skilled labor share will increase the technology growth rate and lower the pollution growth rate, leading to a higher long-run sustainable growth rate.

Changes in the endowments of skilled and unskilled labor have exactly opposite effects on sustainable growth. By assumption, for any given endowment of total population, a higher skilled labor endowment leads to a higher share of skilled labor, $S$. Notice that the skilled labor share in the manufacturing sector, $h^0_M$, is constant ($h^0_M$ depends only on the parameters due to the Cobb-Douglas production function), therefore the additional skilled labor will be absorbed by the R&D sector which leads to a higher technology growth rate $g_A$. At the same time, the decline in unskilled labor will lead to a lower pollution growth rate even without any abatement activity. These two changes will lead to a higher long-run sustainable growth. Proposition 1-3 highlights the importance of education and migration. If a country can devote more resources to education or allow more skilled immigrants to increase its skill abundance, it can achieve higher long-run sustainable growth. Therefore, both education and immigration of skilled labor are utility growth improving.\(^9\)

Parameter $\beta$ captures the complexity and difficulty of R&D technology. An increase in this parameter means that it is more difficult to develop new technology, using the same amount of per-capita skilled labor. This will lead to a lower growth rate of technological progress. Some skilled labor will move from the R&D sector to the manufacturing sector, resulting in a lower technology growth rate, a higher pollution growth rate and a lower long-run sustainable growth rate.

\(^9\) Notice that if the unskilled labor share increases, per capita output and consumption at any point in time will increase, but it is a level effect. The rate of growth of final goods production will decrease over time.
Parameter $\alpha$ captures the productivity of skilled labor in manufacturing. A higher value of $\alpha$ implies that skilled labor will move from R&D to manufacturing. This shift will generate a level effect resulting in higher per capita output and consumption. However, in the long-run, the per-capita output growth rate will be lower and the pollution growth rate will be higher. The same effects occur when consumers care more about current relative to future consumption (i.e., have a higher subjective discount rate $\rho$). Skilled labor will shift from R&D to manufacturing to produce more output for current consumption at the cost of a lower long-run sustainable growth rate.

Parameters $\phi_1$ and $\phi_2$ capture the pollution intensity associated with skilled and unskilled labor employed in manufacturing. Different levels of $\phi_1$ and $\phi_2$ will not affect the allocation of labor or the economic growth rate; however, higher levels of $\phi_1$ and $\phi_2$ will lead to a higher pollution growth rate, and in turn lower the sustainable growth rate. If $\phi_1$ and $\phi_2$ are too high, that can even lead to a zero long-run sustainable growth rate.

**First-Best Solution**

In this section, I explore the balanced growth properties of the model when all allocation decisions are made by a benevolent social planner. Suppose the social planner takes care of the pollution externality and optimally allocates skilled labor among three activities: manufacturing, technology improvements and pollution abatement. Unskilled labor is divided between the manufacturing sector and the pollution abatement sector. The first-best solution can be obtained by assuming that the social planner's objective is to maximize the discounted utility of a representative household:
\[ U = \int_0^\infty e^{-(\rho-n)\tau} [\ln c(t) - \varepsilon \ln Z(t)] dt , \tag{1-26} \]

subject to,

\[ c(t) = A(t) h_M^{\alpha} l_M^{1-\alpha} , \tag{1-27} \]

\[ \dot{A}(t) = A(t) H_A / X(t) = A \frac{h_A}{\beta} , \tag{1-28} \]

\[ \dot{Z}(t) = \left[ \phi h_M + \phi z l_M - \gamma h_Z l_Z^{1-\sigma} \right] Z(t) , \tag{1-29} \]

and two full-employment conditions,

\[ S = h_M + h_A + h_Z , \tag{1-30} \]

\[ 1 - S = l_M + l_Z . \tag{1-31} \]

In this economy, all output from production is consumed at the same time and technology improvement depends on the per-capita skilled labor devoted to the R&D sector. These conditions are exactly the same as in the decentralized economy. The only difference between the first-best and decentralized economy solutions is that the social planner takes into account the environmental externality which in turn affects the pollution and sustainable growth rates.

At the first-best steady state solution, the allocation of per capita skilled and unskilled labor in the manufacturing sector, \( h_M^* \), \( l_M^* \), R&D sector, \( h_A^* \), and the pollution abatement sector, \( h_Z^* \), \( l_Z^* \), are all constant and given by (derivation shown in Algebraic Details):

\[ h_M^* = \alpha \beta (\rho - n) - \frac{\phi \varepsilon \alpha \beta^2 (\rho - n)}{\beta \phi \varepsilon + 1} , \tag{1-32} \]
\[
I_M^* = \frac{(\rho - n)(1 - \alpha)}{\varepsilon[\phi + \gamma(1 - \sigma)(\varepsilon\sigma\beta)^{1-\sigma}]}, \tag{1-33}
\]

\[
h^*_d = S - \alpha\beta(\rho - n) + \frac{\phi\varepsilon\sigma\beta^2(\rho - n)}{\beta\phi + 1} - (1 - S)(\varepsilon\sigma\beta)^{1-\sigma} + \frac{(\rho - n)(1 - \alpha)(\varepsilon\sigma\beta)^{1-\sigma}}{\varepsilon[\phi + \gamma(1 - \sigma)(\varepsilon\sigma\beta)^{1-\sigma}]} , \tag{1-34}
\]

\[
h^*_z = (1 - S)(\varepsilon\sigma\beta)^{1-\sigma} - \frac{(\rho - n)(1 - \alpha)(\varepsilon\sigma\beta)^{1-\sigma}}{\varepsilon[\phi + \gamma(1 - \sigma)(\varepsilon\sigma\beta)^{1-\sigma}]} , \tag{1-35}
\]

and,

\[
I_Z^* = 1 - S - \frac{(\rho - n)(1 - \alpha)}{\varepsilon[\phi + \gamma(1 - \sigma)(\varepsilon\sigma\beta)^{1-\sigma}]}. \tag{1-36}
\]

In the first-best solution, skilled and unskilled labor can be allocated to abate pollution. In the manufacturing sector, both skilled and unskilled labor shares are positive, and in general are less than or equal to the decentralized economy’s shares of both types of labor. The first-best level of per capita skilled labor in the production of final goods (given by equation (1-32)) is less than that of the decentralized economy (given by equation (1-20)). The difference between the first-best level and the decentralized equilibrium level of per-capita skilled labor is captured by the last term in equation (1-32) which is related to the environmental externality. As the relative disutility of pollution \(\varepsilon\) falls, both per-capita skilled and unskilled labor in manufacturing increase towards the equilibrium level. Notice in the trivial case when \(\varepsilon\) approaches zero, the first-best solution is identical to the equilibrium solution. In the R&D sector and the pollution abatement sector, whether the shares are positive or negative depends on the skilled labor share \(S\) and the unskilled labor share \(1 - S\). Only when
$1 - S > \frac{(\rho - n)(1 - \alpha)}{\varepsilon[\phi_2 + \gamma(1 - \sigma)(\varepsilon \sigma \gamma \beta)^{1 - \sigma}]}$ will skilled labor and unskilled labor be allocated to the pollution abatement sector. So if the initial unskilled labor share $1 - S$ is low, or unskilled labor is not so polluting ($\phi_2$ is low), or the disutility of pollution ($\varepsilon$) is low or some policy restraints are binding, then the social planner may not allocate resources to abate pollution at all. This situation, where pollution is not abated at all, happens under certain conditions. For example, when the initial skilled labor share $S$ is large enough, there is no need to abate the pollution in this economy since the output growth will outweigh the negative effect of pollution. Lower productivity of unskilled labor in manufacturing (measured by $1 - \alpha$), higher productivity of unskilled labor in pollution abatement (measured by $1 - \sigma$) and more effective abatement activity (higher $\gamma$) will make abatement activity more likely.

**Proposition 1-4:** The growth rate of technology $g_A^*$ in the first-best solution cannot be ranked against the decentralized equilibrium growth rate $g_A^0$: $g_A^* \geq g_A^0$. The growth rate of pollution in the first-best solution is below its decentralized-equilibrium level: $g_z^* < g_z^0$. The sustainable growth rate in the first-best solution is unambiguously higher than the decentralized-equilibrium sustainable growth rate: $g_u^* > g_u^0$.

The growth rate of technology in the first-best solution is given by:

$$g_A^* = \frac{S}{\beta} - \alpha(\rho - n) + \frac{\phi_2 \alpha \beta (\rho - n)}{\beta \phi_2 \varepsilon + 1} - \frac{(1 - S)(\varepsilon \sigma \gamma \beta)^{1 - \sigma}}{\beta} + \frac{(\rho - n)(1 - \alpha)(\varepsilon \sigma \gamma \beta)^{1 - \sigma}}{\beta \varepsilon[\phi_2 + \gamma(1 - \sigma)(\varepsilon \sigma \gamma \beta)^{1 - \sigma}]}.$$ (1-37)

In both the decentralized and first-best solutions, the growth rate of technology is proportional to per-capita skilled labor in the R&D sector. In the first best solution, the
technology growth rate may be larger, smaller, or equal to the growth rate associated with the decentralized economy, depending on whether the last three terms in equation (1-37) are positive, negative or zero, because the first two terms are equal to the decentralized equilibrium technology growth rate. Some of the skilled labor released from the decentralized manufacturing sector goes into the abatement sector, but some may also be allocated by the social planner to non-polluting technology accumulation. In this case, the first best technology growth rate is higher: \( g_A^* > g_A^0 \). However, under other circumstances pollution abatement incentives may draw skilled labor out of both the manufacturing and R&D sectors, leading to lower economic growth: \( g_A^* < g_A^0 \). Thus, neither per capita skilled labor in the R&D sector, nor the growth rate of technology can be ranked unambiguously against the decentralized solution. We can vary the value of the skilled labor productivity parameter \( \sigma \) in the abatement sector to rank the equilibrium and first-best growth rates of technology as an illustration. It can be shown that the first-best technology growth rate \( g_A^* \) is a monotonic decreasing function of the parameter \( \sigma \). Notice that per capita skilled labor in the manufacturing sector \( h_m^* \) is independent of \( \sigma \). Therefore when the skilled labor productivity parameter \( \sigma \) is approaching 0, the social planner will allocate a very small fraction of skilled labor to the abatement sector and allocate most skilled labor to the R&D sector, leading to a higher technology growth rate than in the decentralized economy. As \( \sigma \) increases, the social planner will direct more skilled labor to the abatement sector and less to the R&D sector, causing the technology growth rate to decrease. If \( \sigma \) is large enough, the technology growth rate will be lower than in the decentralized economy. Actually, there is a critical value of \( \sigma \) which satisfies
\[
\frac{\phi \epsilon \alpha \beta (\rho - n)}{\beta \phi \epsilon + 1} + \frac{(\rho - n)(1 - \alpha)(\epsilon \sigma g)_{1 - \sigma}}{\beta \epsilon [\phi_2 + \gamma (1 - \sigma)(\epsilon \sigma g)_{1 - \sigma}]} = \frac{(1 - S)(\epsilon \sigma g)_{1 - \sigma}}{\beta}.
\]

Given all other parameters, denote this critical value as \( \sigma^* \). When \( \sigma = \sigma^* \), the technology growth rates in the decentralized economy and in the one with a social planner are the same: \( g^*_d = g^*_A \).

The growth rate of pollution in the first-best solution is given by:

\[
g^*_z = \frac{\phi \alpha \beta (\rho - n)}{\phi \epsilon + 1} - (1 - S)\gamma (\epsilon \sigma g)_{1 - \sigma} + \frac{(\rho - n)(1 - \alpha)[\phi_2 + \gamma (\epsilon \sigma g)_{1 - \sigma}]}{\epsilon [\phi_2 + \gamma (1 - \sigma)(\epsilon \sigma g)_{1 - \sigma}]}.
\]  

(1-38)

\( g^*_z \) can be optimally positive, negative or zero depending on the following condition:

\[
(1 - S)\gamma (\epsilon \sigma g)_{1 - \sigma} < \frac{\phi \alpha \beta (\rho - n)}{\phi \epsilon + 1} + \frac{(\rho - n)(1 - \alpha)[\phi_2 + \gamma (\epsilon \sigma g)_{1 - \sigma}]}{\epsilon [\phi_2 + \gamma (1 - \sigma)(\epsilon \sigma g)_{1 - \sigma}]} \quad (1-39)
\]

If \( g^*_z \) is optimally negative or zero, it is obviously less than the equilibrium pollution growth rate \( g^*_z \) in the setting without a social planner, as in that case the pollution growth rate is always positive (given by equation (1-23)). I prove in proposition 1-4 that even when \( g^*_z \) is optimally positive, it is less than \( g^*_z \). The reason is very simple: the social planner allocates skilled labor and unskilled labor to the pollution abatement sector to decrease emissions. Furthermore, skilled and unskilled labor that are polluting in the manufacturing sector are less than those in the decentralized economy.

The sustainable growth rate in the first-best solution is given by:
The sustainable growth rate in the first-best solution is unambiguously higher than the equilibrium sustainable growth rate: $g_u^* > g_u^0$. The social planner can allocate resources to decrease pollution growth. The economic growth may be higher or lower than in the decentralized solution depending on the parameter values. However, because the negative externality of pollution is internalized, the sustainable growth rate is unambiguously higher.

**Proposition 1-5:** In the first-best solution, if the population is growing at a higher rate, the pollution growth rate is lower, leading to a higher sustainable growth rate. However, the effect on the technology growth rate is ambiguous.

If the population is growing at a higher rate, the social planner will allocate less skilled and unskilled labor in the manufacturing sector and more in the pollution abatement sector, causing the pollution growth rate to be lower. Because per-capita skilled labor in the R&D sector $h_{Ah}$ depends on the total per-capita skilled labor $S$, per-capita skilled labor in the manufacturing sector $h_{Mh}$ and per-capita skilled labor in the pollution abatement sector $h_{Zh}$, the effect of higher population growth on the technology growth rate is ambiguous. However, as I proved in proposition 1-5, the gain in utility from lower pollution dominates the reduction in the technology growth rate, leading to a higher sustainable growth rate.
Proposition 1-6: In the first-best solution, an increase in skill abundance $S$ will increase the technology and the pollution growth rates, leading to an ambiguous effect on the economy’s sustainable growth rate.

Unlike the decentralized economy, increasing the skilled labor endowment will increase the first-best pollution growth rate. Higher skilled labor abundance will not affect the per capita skilled and unskilled labor in the manufacturing sector. All the additional skilled labor will be devoted to the R&D sector. Further, because the unskilled labor share is lower in the pollution abatement sector, per capita unskilled labor will be lower as well. This in turn requires less per capita skilled labor due to the Cobb-Douglas production function. The amount of skilled labor released from the pollution abatement sector will also be devoted to the R&D sector. Therefore, the technology growth rate will be higher. Since both per capita skilled and unskilled labor are lower in the pollution abatement sector, the pollution growth rate will be higher as well. Thus, the effect on the sustainable growth rate is ambiguous depending on which force is stronger.

Second-Best Outcomes

In this section, I explore the optimal solution if there is a prohibition placed on pollution abatement. As mentioned in section of first-best solution, under some circumstances, the social planner may not allocate resources to abate pollution at all. It is likely that in less developed countries, governments will take economic growth as their priority. Suppose the social planner takes the pollution externality into account when she maximizes the representative consumer’s utility, but she does not allocate any labor to abate the pollution. Now the social planner’s objective is to maximize the discounted utility of a representative household as following:
\[ U = \int_0^\infty e^{(\rho - n)t} [\ln c(t) - \ln Z(t)] dt, \quad (1-41) \]

Subject to,
\[ c(t) = A(t) h_M^{\alpha} h_M^{1-\alpha}, \quad (1-42) \]
\[ A(t) = A(t) H_A / X(t) = A h_A / \beta, \quad (1-43) \]
\[ Z(t) = \left[ \phi h_M + \phi_2 l_M \right] Z(t), \quad (1-44) \]

and two full employment conditions,
\[ S = h_M + h_A, \quad (1-45) \]
\[ 1 - S = l_M. \quad (1-46) \]

In this economy where pollution abatement is prohibited, at the steady state, the allocation of per capita skilled labor in the manufacturing sector, \( h_M^{SB} \), in the R&D sector, \( h_A^{SB} \), the growth rate of technology, \( g_A^{SB} \), the growth rate of pollution emissions, \( g_Z^{SB} \), and the sustainable growth rate of this economy, \( g_U^{SB} \), are all constant and given by (derivation shown in Algebraic Details):
\[ h_M^{SB} = \frac{\alpha \beta (\rho - n)}{1 + \beta \varepsilon \phi_i}, \quad (1-47) \]
\[ h_A^{SB} = S - h_M^{SB} = S - \frac{\alpha \beta (\rho - n)}{1 + \beta \varepsilon \phi_i}, \quad (1-48) \]
\[ g_A^{SB} = \frac{h_A^{SB}}{\beta} = \frac{S}{\beta} - \frac{\alpha (\rho - n)}{1 + \beta \varepsilon \phi_i}, \quad (1-49) \]
\[ g_Z^{SB} = \phi h_M^{SB} + \phi_2 l_M^{SB} = \frac{\alpha \beta \phi_i (\rho - n)}{1 + \beta \varepsilon \phi_i} + \phi_i (1 - S), \quad (1-50) \]

and,
\[ g^*_u = \frac{S}{\beta} - \alpha(\rho - n) \frac{\varepsilon \alpha \beta \phi_i (\rho - n)}{1 + \beta \varepsilon \phi_i} - \varepsilon \phi_2 (1 - S). \]  

(1-51)

**Proposition 1-7:** The growth rate of technology \( g^*_{A} \) in the second-best solution is higher than the equilibrium growth rate \( g^0_{A} \): \( g^*_{A} > g^0_{A} \). The growth rate of pollution in the second-best solution is reduced below the equilibrium level: \( g^*_{Z} < g^0_{Z} \). The sustainable growth rate in the second-best solution is unambiguously higher than the equilibrium sustainable growth rate: \( g^*_{u} > g^0_{u} \).

**Proposition 1-8:** The growth rate of technology \( g^*_{A} \) in the second-best solution is higher than the first-best growth rate \( g^*_{A} \): \( g^*_{A} > g^*_{A} \). The growth rate of pollution in the second-best solution is also higher than the efficient level: \( g^*_{Z} > g^*_{Z} \). The sustainable growth rate in the second-best solution is unambiguously lower than the efficient sustainable growth rate: \( g^*_{u} < g^*_{u} \).

When pollution abatement is prohibited, technological progress is faster than in either the equilibrium solution or the first-best solution. In this specification, the social planner has an incentive to internalize the externality of pollution emissions. However, since no labor can be devoted to the pollution abatement sector, the social planner’s objective can only be achieved by reducing unskilled labor in the manufacturing sector. All unskilled labor that optimally would have been used in pollution abatement, as well as some additional unskilled labor being released from manufacturing, will move to the R&D sector and therefore increase the economic growth rate.
Conclusions

This chapter explores the tradeoff between economic growth and environmental degradation and compares the optimal solutions in a decentralized economy with an economy with a social planner. Without government intervention, a decentralized economy will have a faster pollution growth rate. Households do not internalize the relationship between environmental quality and economic productivity, pollution would increase without bound and no investment would be made in abatement technology. An economy with a social planner will have unambiguously a higher sustainable growth rate. However, the rate of technology accumulation cannot be ranked.

In addition, this chapter focuses on the relationship between population growth and sustainability. Unlike other studies which suggest that the demographic transition to lower fertility is essential to sustainable development, this chapter suggests that population growth could boost technological progress and generate faster economic growth which would outweigh the disutility from pollution. Therefore a positive sustainable growth rate is achievable. Moreover, in an economy with a social planner, an explicit pollution abatement sector makes it possible to decrease the pollution growth rate below the equilibrium level.

Algebraic Details

In this section, we include the proofs and algebraic details for Chapter 1.

Market Equilibrium Solution:

Set up the current-value Hamiltonian:

\[
H = \ln(Ah_m^{\alpha}l_m^{1-\alpha}) - \varepsilon \ln Z + \mu Ah_M / \beta = \ln(Ah_m^{\alpha}l_m^{1-\alpha}) - \varepsilon \ln Z + \mu A(S - h_M) / \beta ,
\]

where \(\mu\) denotes the shadow price associated with technology accumulation.
The first order conditions are:

\[
H_{h_M} = \frac{\alpha}{h_M} - \frac{\mu A}{\beta} = 0 ,
\]

\[
\frac{\mu}{\mu} = \rho - n - \frac{1}{\mu A} - \frac{S - h_M}{\beta} .
\]

The growth rate of technology \( g_A \) and its shadow price \( \mu \) are constant along the balanced growth path. Taking logarithms and differentiating with respect to time, we have:

\[
\frac{\dot{A}}{A} + \frac{\mu}{\mu} = 0 .
\]

From the above conditions, we can obtain \( \rho - n - \frac{1}{\mu A} = 0 \). Together with the first order conditions, we can solve for equations (1-20)-(1-24).

**The First-Best Solution:**

Set up current-value Hamiltonian:

\[
H = \ln(A h_M^{1-\sigma}) - \varepsilon \ln Z + \mu A \frac{h_M}{\beta} + \tau Z (\phi h_M + \phi h_Z - \gamma h_Z^{1-\sigma})
\]

\[+ \lambda_h (S - h_M - h - h_Z) + \lambda \left( 1 - s - l - l_Z \right), \]

where \( \mu \) and \( \tau \) are the shadow prices of technology accumulation and pollution emissions respectively and where \( \lambda_h \) and \( \lambda_i \) are the Lagrange multipliers associated with the full employment conditions for skilled and unskilled labor respectively.

The first order conditions are:

\[
H_{h_M} = \frac{\alpha}{h_M} + \tau \phi Z - \lambda_h = 0 ,
\]
The growth rates of technology, consumption and pollution emissions are constant along the balanced growth path. Taking logarithms and differentiating with respect to time, we have
\[ \frac{\dot{\mu}}{\mu} = \rho - n - \frac{1}{\mu A} - \frac{h_i}{\beta}, \]
and,
\[ \frac{\dot{\tau}}{\tau} = \rho - n - \frac{\varepsilon}{\tau Z} - \phi_i h_M - \phi_z I_M + \gamma h^Z Z^{-\sigma}. \]

Together with the first order conditions, we can solve for equations (1-32)-(1-36).

**The Second-Best Solution:**

Set up the current value Hamiltonian:
\[ H = \ln(A h_M^{1-\sigma}) - \varepsilon \ln Z + \mu A \frac{h_i}{\beta} + \tau Z (\phi_i h_M + \phi_z I_M) + \lambda_h (S - h_M - \lambda_h) , \]

where \( \mu \) and \( \tau \) are the shadow prices of technology accumulation and pollution emissions respectively and where \( \lambda_h \) is the Lagrange multiplier associated with the full employment condition for skilled labor.
The first order conditions are:

\[ H_{h_{h}} = \frac{\alpha}{h_{M}} + \tau \phi_{Z} - \lambda_{h} = 0 , \]

\[ H_{h_{z}} = \frac{\mu A}{\beta} - \lambda_{z} = 0 , \]

\[ \frac{\mu}{\mu} = \rho - n - \frac{1}{\mu A} - \frac{h_{z}}{\beta} , \]

and,

\[ \frac{\tau}{\tau} = \rho - n + \frac{e}{\tau Z} - \phi_{h_{z}} - \phi_{l_{z}} . \]

Using these first order conditions, we can solve for equations (1-47)-(1-51).

**Comparative Statics:**

(Proof for Proposition 1-2, 1-3 and 1-6)

I have derived the long-run growth rate of technology growth, the growth rate of pollution emissions and the sustainable growth rate under three different settings: the equilibrium, the first-best and the second-best. The following results can be used to show the effects on these growth rates when the population growth rate and skilled labor share change:

\[ \frac{dg_{A}}{dn} > 0 , \quad \frac{dg_{A}^*}{dn} >= 0 , \quad \frac{dg_{A}^{sb}}{dn} > 0 ; \]

\[ \frac{dg_{Z}}{dn} < 0 , \quad \frac{dg_{Z}^*}{dn} < 0 , \quad \frac{dg_{Z}^{sb}}{dn} < 0 ; \]

\[ \frac{dg_{U}}{dn} > 0 , \quad \frac{dg_{U}^*}{dn} > 0 , \quad \frac{dg_{U}^{sb}}{dn} > 0 ; \]

\[ \frac{dg_{A}}{dS} > 0 , \quad \frac{dg_{A}^*}{dS} > 0 , \quad \frac{dg_{A}^{sb}}{dS} > 0 ; \]
\[
\frac{dg^0_Z}{dS} < 0, \quad \frac{dg^*_Z}{dS} > 0, \quad \frac{dg^{SB}_Z}{dS} < 0;
\]

and,

\[
\frac{dg^0_U}{dS} > 0, \quad \frac{dg^*_U}{dS} >= 0, \quad \frac{dg^{SB}_U}{dS} > 0.
\]
CHAPTER 2
HETEROGENEOUS POLLUTERS AND ENVIRONMENTAL STANDARDS

Introduction

Do more stringent environmental standards lower an industry’s productivity and make firms less competitive? The relationship between environmental protection and economic competitiveness has received increasing attention from both scholars and policy makers in the past several decades. On one hand, the Porter Hypothesis suggests that strict environmental regulations often enhance the competitiveness of the domestic industries against their foreign rivals. Porter and Van der Linde (1995) argue that tough standards trigger technological innovation that may result in inexpensive ways to reduce pollution. The nations with the most rigorous regulations often lead in the exporting of those products. On the other hand, economists have been skeptical of this hypothesis. Palmer et al. (1995) survey firms affected by regulation and find that most firms say that the net cost of regulation is indeed positive. We observe that industries have opposed stricter environmental regulations. The automobile industry has been fighting mandates to improve fuel efficiency, even though meeting them could stimulate innovations that make products more competitive.

Transportation is a major source of air pollution in the United States. Vehicle emissions contribute to health and environmental problems such as air toxics, urban smog, and global warming. In numerous cities across the country, the personal automobile is the single greatest polluter, as emissions from millions of vehicles on the road add up. Driving a private car is probably a typical citizen’s most polluting daily activity. The vehicles release over 1.7 billion tons of $CO_2$ into the atmosphere each year contributing to global climate change. On average, each gallon of gasoline burned
generates 20 pounds of $CO_2$ which leads to 6 to 9 tons of $CO_2$ each year for a typical vehicle. For a typical household, vehicle emissions contribute to 51% of $CO_2$ emissions, followed by appliances (26%) and heating and cooling (18%). Congress first adopted the fuel economy standards - known as CAFE (Corporate Average Fuel Economy) standards - in 1975 as a response to the oil embargo of 1973-1974. CAFE doubled new car fuel mileage to 27.5 mpg by 1985. In May 2009 the Obama administration announced the greenhouse gas emissions standard for cars. The standard is a joint rule by the Environmental Protection Agency (EPA) and the Department of Transportation (DOT) and will require cars to average 35.5 mpg by 2016, four years earlier than under previous fuel economy requirements.

The purpose of this chapter is to develop a model to study the effect of more stringent environmental standards on firms' profitability, pollution and consumers' welfare while emphasizing the importance and the nature of uncertainty in environmental R&D. Investment in environmental R&D aimed at improving firms' environmental performance is common in U.S. manufacturing industries. Scott (2003) surveys a group of manufacturing companies and finds that on average, 23.9% of a firm's total R&D expenditures are channeled towards environmental projects. Moreover, over one-half of the firms participating in the survey indicate that their environmental R&D projects are undertaken as a response to specific environmental legislation. For example, Goldberg(1998) finds that CAFE offers incentives for producers to develop environmentally friendlier technologies and vehicles.

Environmental R&D is generally modeled as a response to government regulation, aiming at reducing firms' compliance costs. Environmental R&D could reduce the cost of
abatement or reduce the amount of polluting inputs used in the production process. (See Xepapadeas and Zeeuw (1999), and Bovenberg and Smulders (1995)). I offer an alternative approach in this chapter: environmental R&D is modeled as a compulsory investment before any production. Without this investment, firms will not be able to discover and produce any products. All firms have to pay the same amount of environmental R&D $f_e$ but discover varieties with different environmental quality. The amount of environmental R&D is stochastically related to the level of environmental quality. Different levels of environmental quality are obtained due to the uncertainty of the R&D process and the outcomes of environmental quality are realized by a commonly known distribution.

Recent theory has shown that differences in firm-specific variables will lead to differences in prices and therefore firms' revenues and profits. For example, in Melitz (2003) and Melitz and Ottaviano (2007), firms are heterogeneous in their productivity. More productive firms have lower marginal costs and are able to charge lower prices to earn higher revenues and profits. A number of recent models have developed firm heterogeneity in their quality.¹ For example, Dinopoulos and Unel (2010) introduce entry-deterring limit-pricing strategies where higher quality firms will be able to charge higher prices and markups to earn higher revenues and profits. In this chapter, firm heterogeneity comes from an R&D structure that follows the literature. When firms engage in R&D to discover new products, they face uncertainty with respect to the future level of environmental quality contained in their products. In the automobile industry, there is firm heterogeneity in environmental quality: different brands or models

often have different levels of environmental quality. For example, a 2010 Toyota Prius
gets 48 MPG (miles per gallon), a 2010 Ferrari 599 GTB Fiorano gets 15 MPG and a
Mercedes-Benz SLK350 gets 25 MPG. Some brands are constrained by the
environmental standards and the environmental quality of some brands exceeds the
environmental standards. Therefore, when regulators decide to impose stricter
standards, firms that no longer meet the standards will have to exit the market. This
model is suitable to take into account firm heterogeneity in environmental quality. We
have not seen many papers addressing the impact of environmental policy on
heterogeneous firms. Yokoo (2009) uses a monopolistically competitive firm setup and
studies the effect of an environmental tax on productivity. He finds that an increase in
the tax rate will drive up average productivity and lower each firm's revenue and profit.
However, his paper did not study the uncertainty of the environmental R&D process and
the effect of environmental standards is also not discussed.

Following the literature, we assume that firms pay a fixed entry cost to invest in
environmental R&D to be able to draw an environmental quality parameter from a
common and known distribution. A new utility function is introduced to account for the
facts that: (1) consumers prefer goods with better environmental quality; and (2)
pollution emissions reduce utility. The regulator sets an environmental standard and this
standard is strictly enforced. Firms with very low environmental quality will not enter the
market since they do not meet the standard. We find that firms with low environmental
quality will be forced to exit the market when the regulator imposes a stricter standard
and firms with high environmental quality stay in the market, produce heterogeneous
goods and generate less pollution per unit of output. With a stricter standard, there will
be fewer firms in the market at the steady-state equilibrium, and firms’ average profits will be higher since the competition will be less intense. They will generate less pollution per unit of output and the overall effect on the welfare of consumers will be ambiguous. An optimal standard is also calculated using a Pareto distribution.

The Model

Consumers

Assume a country has $L$ consumers with identical preferences. The preferences for a representative consumer are given by

$$U = Q - Z$$

(2-1)

where $Q$ is the aggregate consumption over a continuum of products that is indexed by $\omega$ and is defined as a C.E.S function

$$Q = \left[ \int_{\omega \in \Omega} \left[ \lambda(\omega)^{\alpha} \frac{q(\omega)}{L} \right]^\rho \, d\omega \right]^{1/\rho}$$

(2-2)

where $0 < \rho < 1$, so that the elasticity of substitution between any two products is

$$\sigma = \frac{1}{1 - \rho} > 1.$$ $q(\omega)$ is the aggregate consumption of brand $\omega$, $\Omega$ is the set of varieties available to consumers and $\lambda(\omega) > 1$ denotes the time-invariant environmental quality of brand $\omega$. Values of environmental quality $\lambda(\omega)$ depend on firms’ R&D ability. Motivated by the automobile industry, we can consider the environmental quality as the fuel-efficiency of different models of vehicles, so the model with a higher level of environmental quality has better fuel economy, i.e., higher miles per gallon (MPG). If a firm develops an electronic vehicle, $\lambda(\omega)$ is very large.$^2$ $\alpha > 0$ is a parameter capturing

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2 Electronic vehicles generate other types of pollutions that for simplicity we do not discuss.
the intensity of consumers' preference for the differentiated goods with some degree of 
environmental quality. According to a 2009 survey by the Consumer Reports National 
Research Center, the most important considerations for today's new-car buyers are fuel 
economy, quality, safety, price, and value. Many consumers are willing to pay higher 
prices and even submit to a waiting list to purchase the environmentally friendly hybrid 
vehicles. Higher $\alpha$ means that environmental quality counts more in a representative 
consumer's preference for the differentiated goods. When $\alpha$ is approaching zero, it 
means that consumers do not care about environmental quality contained in a product 
at all.

The consumption of these products generates pollution. $Z$ is defined as the total 
amount of pollution summed over all varieties consumed in a country:

$$Z = \int_{\omega \in \Omega} z(\omega) d\omega$$  \hspace{1cm} (2-3)

The amount of pollution generated from consuming brand $\omega$ by all consumers is:

$$z(\omega) = \varepsilon \lambda(\omega)^{-\beta} q(\omega)$$  \hspace{1cm} (2-4)

where $\beta > 0$ is a parameter capturing the pollution intensity. Higher $\beta$ means that for a 
given environmental quality, consuming the same amount of a brand will generate less 
pollution. When $\beta$ approaches infinity, there will be no pollution; when $\beta$ approaches 
zero, the environmental quality does not affect pollution. Pollution from consuming a 
brand becomes proportional to the quantity demanded. $\varepsilon > 0$ is a parameter capturing 
this relationship, indicating that consuming 1 unit of brand $\omega$ generates $\varepsilon$ units of 
pollution if $\beta = 0$. Given parameters $\beta$ and $\varepsilon$, if a brand $\omega$ has a higher level of 
environmental quality, consuming one unit of this product will generate less pollution.
Consuming varieties with higher environmental quality increases consumer utility in two ways: first, a representative consumer has preferences for those goods; and second, consuming the same amount of goods with higher environmental quality generates less pollution.

The representative consumer assumes that her own behavior does not affect aggregate pollution, so she takes aggregate pollution as given. Maximize her utility (2-1) subject to a budget constraint:

$$\int_{\omega \in \Omega} p(\omega) \frac{q(\omega)}{L} d\omega = E$$  \hspace{1cm} (2-5)

where $E$ is per-capita consumer expenditure summed over all varieties, $L$ is the number of consumers in the market, $p(\omega)$ is the corresponding price of brand $\omega$ and $q(\omega)$ is the aggregate consumption of brand $\omega$.

For a particular brand $\omega$, aggregate consumption $q(\omega)$ and aggregate expenditure $r(\omega)$ are:

$$q(\omega) = ELP^{\sigma-1} p(\omega)^{-\sigma} \lambda(\omega)^{\sigma(\sigma-1)}$$ \hspace{1cm} (2-6)

$$r(\omega) = p(\omega)q(\omega) = ELP^{\sigma-1} p(\omega)^{1-\sigma} \lambda(\omega)^{\sigma(\sigma-1)}$$ \hspace{1cm} (2-7)

where the price index adjusted for environmental quality (the green price index) is defined as:

$$P = \left[ \int_{\omega \in \Omega} \left( \frac{p(\omega)}{\lambda(\omega)^{\sigma}} \right)^{1-\sigma} d\omega \right]^{1/(1-\sigma)}$$ \hspace{1cm} (2-8)

When consumers do not have any preference for the environmentally friendly products, $\alpha = 0$, the green price index collapses to the standard aggregate price index as shown in Melitz (2003). The aggregate consumption and the optimal expenditure for
brand $\omega$ both increase in aggregate consumer expenditure $EL$, the green price index $P$ and its level of environmental quality $\lambda(\omega)$; and both decrease in its own price $p(\omega)$.

**Firms**

Labor is the only factor of production, with each worker supplying one unit of labor, so the labor supply is given by the number of consumers, $L$. There is a continuum of firms and each firm chooses to produce a different variety. Initially, the regulator sets an environmental standard $\bar{\lambda}$ and firms have to invest in environmental R&D before they start producing. In order for any firm to begin producing a variety, it will first invest a fixed entry cost $f_c > 0$, that is measured in units of labor and is interpreted as the number of R&D researchers required by the entrant to discover a new variety. All firms pay the same entry cost $f_c$ but will discover varieties with different environmental quality. Therefore, we interpret this fixed entry cost as environmental R&D. After incurring environmental R&D, firms draw their environmental quality parameter, $\lambda$, out of a commonly known distribution. This process captures the uncertainty of environmental R&D. For any producing firm, assume that marginal cost is an increasing function of environmental quality: $MC = \lambda^\gamma$, where $\gamma > 0$. Further, assume that there is no fixed production cost once the variety has been discovered. Therefore, in order to produce $q$ units of output, $l = \lambda^\gamma q$ units of labor are required. Because marginal cost and total cost both increase in environmental quality, it will cost more for those firms with higher environmental quality levels to produce the same amount of output. For the remainder of this chapter, products are labeled based on their environmental quality levels since each brand is associated with a unique environmental quality level.
Regardless of the differences in environmental quality, each firm faces a residual demand curve with constant elasticity because of the C.E.S consumption index. The producing firms maximize their profits by taking the number of firms \( M \) and the green price index \( P \) as given. A firm with environmental quality \( \lambda \) will set the profit-maximizing price as a constant markup over its marginal cost

\[
p(\lambda) = \frac{\lambda^\gamma}{\rho}
\]  

(2-9)

where we normalize the wage rate to one \( (w \equiv 1) \). Combine (2-4), (2-6), (2-7) and (2-9), its demand \( q(\lambda) \), revenue \( r(\lambda) \), profit \( \pi(\lambda) \) and pollution \( z(\lambda) \) are given by:

\[
q(\lambda) = EL \rho^{\sigma-1} \lambda^\gamma \rho^a \rho^{(a-\gamma)(\sigma-1)}
\]  

(2-10)

\[
r(\lambda) = p(\lambda)q(\lambda) = EL (P \rho)^{\sigma-1} \lambda^{(a-\gamma)(\sigma-1)}
\]  

(2-11)

\[
\pi(\lambda) = \frac{r(\lambda)}{\sigma} = EL (P \rho)^{\sigma-1} \frac{\lambda^{(a-\gamma)(\sigma-1)}}{\sigma}
\]  

(2-12)

and

\[
z(\lambda) = \epsilon EL \rho^{\sigma-1} \lambda^\gamma \rho^a \rho^{(a-\gamma)(\sigma-1)}
\]  

(2-13)

The ratios of any two firms' outputs, revenues, profits and pollution generated depend only on the ratio of their environmental quality levels:

\[
\frac{q(\lambda_1)}{q(\lambda_2)} = \left( \frac{\lambda_1}{\lambda_2} \right)^{(a-\gamma)(\sigma-1)}
\]  

(2-14)

\[
\frac{r(\lambda_1)}{r(\lambda_2)} = \frac{\pi(\lambda_1)}{\pi(\lambda_2)} = \left( \frac{\lambda_1}{\lambda_2} \right)^{(a-\gamma)(\sigma-1)}
\]  

(2-15)

and

\[
\frac{z(\lambda_1)}{z(\lambda_2)} = \left( \frac{\lambda_1}{\lambda_2} \right)^{(a-\gamma)(\sigma-1)-\beta}
\]  

(2-16)
When $\alpha > \gamma$, the profit function is increasing in the level of environmental quality. Consumers have strong preference for products with better environmental quality. Therefore, higher demand for environmentally friendly products compensates for the fact that it costs firms more to produce these products. A firm with a higher environmental quality level $\lambda$ earns higher revenue because it is able to charge a higher price and make higher profits. If a firm happens to discover a variety with environmental quality equal to the environmental standard, compared to all the producing firms, this firm will make the lowest profit. However, it is not clear whether the consumption of this product causes more or less pollution. If consumers’ preference for environmentally friendly products is strong enough ($\alpha > (\gamma \sigma + \beta) / (\sigma - 1)$), when a product has a high environmental quality level, consumers actually buy more of the product which leads to more pollution. When $\alpha < (\gamma \sigma + \beta) / (\sigma - 1)$, the pollution will be decreasing in the environmental quality. Furthermore, when $\alpha \leq \gamma$, the consumption of a product with higher $\lambda$ will generate less pollution. When $\alpha < \gamma$, the profit function is decreasing in the level of environmental quality. Consumers have a preference for those products with better environmental quality, but not strong enough to compensate for the higher costs associated with the production of those goods. In this case, firms with higher environmental quality earn less revenue and profits. The firm with environmental quality equal to the standard level will make the highest profit compared to all the producing firms, and as $\lambda$ approaches infinity, profit approaches zero. When $\alpha = \gamma$, profit is not directly affected by its environmental quality level at all.
Entry Decisions

The regulator sets an environmental standard $\bar{\lambda}$. This regulated level is strictly enforced so any firm producing a variety with $\lambda < \bar{\lambda}$ will not be able to sell its products at all in the market. Suppose that there are a large number of prospective ex-ante identical entrants. Initially, a firm incurs the fixed entry cost, which is the environmental R&D, $f_e$, then it draws its environmental quality parameter $\lambda$ from a common and known distribution $g(\lambda)$ with positive support over $(0, \infty)$ and with continuous cumulative distribution $G(\lambda)$. The properties of $g(\lambda)$ determine the benefits of entry measured by the relevant expected discounted profits. After observing its environmental quality level $\lambda$, a firm decides whether to exit the market immediately or start producing. If a firm discovers a product with low environmental quality $\lambda < \bar{\lambda}$, it does not meet the environmental standard and will immediately exit and not produce. If a firm discovers a product with environmental quality level equal to or greater than the standard $\lambda \geq \bar{\lambda}$, it will enter the market and make positive profits. Any producing firm that meets the environmental standard is always earning positive profits without the fixed production cost because of the constant markup over marginal cost due to the C.E.S structure.

Each incumbent firm faces a constant probability of death $\delta$ in each period as a result of being hit by a stochastic shock ($0 < \delta < 1$). In the present context, this stochastic shock can be interpreted as changing tastes that eliminate the demand for a particular variety. Since the exit is uncorrelated with the environmental quality, the exit process will not affect the equilibrium environmental quality distribution $\mu(\lambda)$. As in Melitz (2003), the ex-ante probability of drawing an environmental quality level $\lambda$ is governed by the density function $g(\lambda)$ and the ex-ante probability of successful entry.
$p_m = 1 - G(\lambda)$. The equilibrium distribution of environmental quality $\mu(\lambda)$ is then determined by the initial draw, conditional on successful entry $p_m = 1 - G(\lambda)$. Therefore, $\mu(\lambda)$ is the conditional distribution of $g(\lambda)$ on the interval $[\lambda, \infty)$:

$$
\mu(\lambda) = \frac{g(\lambda)}{1 - G(\lambda)}
$$

(2-17)

If the regulator decided to set a higher environmental standard, that the equilibrium distribution of environmental quality $\mu(\lambda)$ would change. It would then be harder for any potential firm to enter the market, the ex-ante probability of successful entry would be lower and the equilibrium distribution would be larger.

**Aggregation**

At the steady-state equilibrium, suppose there are $M$ firms with a distribution $\mu(\lambda)$ of environmental quality levels. The green price index (2-8) becomes

$$
P = \left[ \int_{0}^{\infty} \left( \frac{p(\lambda)}{\lambda^\alpha} \right)^{1-\sigma} M \mu(\lambda) d\lambda \right]^{\frac{1}{1-\sigma}}
$$

(2-18)

Using the pricing rule (2-9), when $\alpha \neq \gamma$, (2-18) can be written as$^3$:

$$
P = \frac{M^{\frac{1}{1-\sigma}}}{\rho} \left[ \int_{0}^{\infty} \lambda^{(\alpha-\gamma)(\sigma-1)} \mu(\lambda) d\lambda \right]^{\frac{1}{1-\sigma}} = \frac{M^{\frac{1}{1-\sigma}}}{\rho} \tilde{\lambda}^{\gamma-\alpha}
$$

(2-19)

where $\tilde{\lambda}$ is defined as

$$
\tilde{\lambda} = \tilde{\lambda}(\lambda) = \left[ \frac{1}{1 - G(\lambda)} \int_{\lambda}^{\infty} \lambda^{(\alpha-\gamma)(\sigma-1)} g(\lambda) d\lambda \right]^{\frac{1}{(\alpha-\gamma)(\sigma-1)}}
$$

(2-20)

$\tilde{\lambda}$ is a weighted average of environmental quality of all produced varieties and can be interpreted as the average or expected environmental quality level. The

$^3$ The case when $\alpha = \gamma$ is trivial. Revenues and profits are not affected by environmental quality.
environmental standard $\lambda$ and the ex-ante distribution $g(\lambda)$ will determine the average environmental quality $\bar{\lambda}$ in equilibrium.

Since any firm that does not meet the environmental standard is not able to enter the market at all, the regulated environmental standard is the minimum environmental quality level of all producing firms and it will be lower than the average environmental quality level. Furthermore, an increase of the standard forces firms with low environmental quality levels to exit the market, which in turn increases the average environmental quality level of all produced varieties. The following lemma summarizes these properties. (See Algebraic Details for proof).

**Lemma 2-1**: The average environmental quality level of all produced varieties in an economy is strictly greater than and increases in the environmental standard, i.e., $\bar{\lambda} > \lambda$ and $\partial \bar{\lambda} / \partial \lambda > 0$.

The green price index is decreasing in the number of firms in the market. When there are more firms in the market, competition gets more intense. Therefore, the price index will be smaller. When $\alpha < \gamma$, the green price index is increasing in the average environmental quality level. Since the costs of production are high, firms charge higher prices. When $\alpha > \gamma$, the green price index is increasing in the average environmental quality level. High demand for products makes it profitable even if firms charge lower prices.

The aggregate revenue and aggregate profit are given by:

$$R = \int_0^\infty r(\lambda) M(\mu(\lambda)) d\lambda$$  \hspace{1cm} (2-21)

and
\[ \Pi = \int_0^\infty \pi(\lambda) M \mu(\lambda) d\lambda \]  

(2-22)

Also, the aggregate quantity, average revenue and profit per firm can be derived (see Algebraic Details):

\[ Q = \rho M \frac{1}{\sigma-\gamma} \tilde{\lambda}^{\sigma-\gamma} \]  

(2-23)

\[ \bar{r} = \frac{R}{M} = r(\tilde{\lambda}) \]  

(2-24)

\[ \bar{\pi} = \frac{\Pi}{M} = \pi(\tilde{\lambda}) \]  

(2-25)

An industry with \( M \) firms with a distribution of environmental quality \( \mu(\lambda) \) that yields the same average environmental quality level \( \tilde{\lambda} \) will have the same aggregate quantity, revenue and profit as an industry with \( M \) representative firms that have the same environmental quality \( \tilde{\lambda} \).

**Free Entry and the Value of the Firms**

A firm producing a variety with environmental quality level \( \lambda \) earns a per-period profit \( \pi(\lambda) \). Since each firm faces a constant probability of death \( \delta \) in each period, the market value of a firm with environmental quality level \( \lambda \) is given by

\[ v(\lambda) = \max \left\{ 0, \sum_{t=0}^\infty (1-\delta)^t \pi(\lambda) \right\} = \max \left\{ 0, \frac{\pi(\lambda)}{\delta} \right\} \].

The second equality follows from the fact that the environmental quality contained in each firm’s product remains constant during its lifetime, so every period it earns the same profit. Because the probability of successful entry is \( 1 - G(\tilde{\lambda}) \), the net benefits of entering the domestic market are equal to the expected value of a firm \( [1 - G(\tilde{\lambda})] \overline{v} \), where \( \overline{v} = \bar{\pi} / \delta \) is the ex-ante value of a
prospective entrant and \( \pi \) is defined by (2-25). Setting the benefits of entry equal to the fixed R&D costs yields the free entry condition:

\[
\pi = \frac{\delta f_e}{1 - G(\lambda)}
\]  

(2-26)

The average profit is solely determined by the probability of death \( \delta \), the fixed environmental R&D \( f_e \) and the environmental standard \( \lambda \). Given the probability of death \( \delta \) and the fixed environmental R&D \( f_e \), if the regulator sets a higher level of environmental standard, then prospective firms are less likely to enter successfully, an entrant would expect there will be fewer firms in the market and its expected value would be higher.

At the steady-state equilibrium, the aggregate variables must remain constant over time, so the number of firms is constant. Therefore in any single period, the number of successful entrants \( p^m M_e \) must be equal to the number of incumbent firms who are forced to exit the market due to a bad shock, i.e., \( p^m M_e = \delta M \), where \( M_e \) is the number of potential entrants and \( p^m M_e \) is the number of successful firms. Because the entering and exiting firms have the same distribution of environmental quality levels, at the steady-state equilibrium the distribution of environmental quality \( \mu(\lambda) \) is not affected by this simultaneous entry and exit. The labor employed by the prospective entrants for environmental R&D to discover the varieties and the labor employed by the incumbent firms for manufacturing are denoted by \( L_e \) and \( L_m \). For the full employment condition to be satisfied, labor demand equals labor supply, i.e., \( L_e + L_m = L \). Total payments to workers in manufacturing are equal to the difference between aggregate revenue and
profit: \( L_m = R - \Pi \). The labor employed by the prospective entrants for environmental R&D to discover the varieties are given by \( L_e = M_e f_e \). Using the aggregate stability condition, \( p_m M_e = \delta M \), and the free entry condition, \( \bar{\pi} = \frac{\delta f_e}{1-G(\bar{\lambda})} \), \( L_e \) can be written as:

\[
L_e = M_e f_e = \frac{\delta M}{1-G(\bar{\lambda})} f_e = M \bar{\pi} = \Pi
\] (2-27)

Thus, the aggregate amount of labor employed by the prospective entrants for environmental R&D equals the level of aggregate profits earned by all producers in the economy. Also, the aggregate revenue \( R = EL = L_m + \Pi = L_m + L_e \) must also equal the total payments to labor \( L \) and is solely determined by the total number of consumers. Per-capita expenditure equals unity due to the choice of labor as the numeraire, i.e., \( E = w \equiv 1 \) and the aggregate revenue \( R = L \). The number of producing firms in any period can then be determined from the average profit using (2-26):

\[
M = \frac{EL}{\bar{\pi}} = \frac{L}{\sigma \bar{\pi}} = \frac{L \left[ 1 - G(\bar{\lambda}) \right]}{\sigma \delta f_e}
\] (2-28)

At the steady-state equilibrium, the number of varieties is determined by the size of the economy, the elasticity of substitution between any two products, the stochastic shock, environmental R&D and the environmental standard. If the size of the economy is larger, there is more labor available to discover the varieties and more labor available for manufacturing. Therefore, there are more varieties produced. If the environmental standard is higher or the required amount of environmental R&D is higher, it would be harder for the potential entrants to enter the market successfully. There will be fewer varieties. With a higher elasticity of substitution and given the average profit \( \bar{\pi} \), the
average revenue will be higher. Since the aggregate revenue $R$ is fixed by the size of the economy, there will be fewer varieties available at the steady-state.

**Welfare**

Both consumers and producers take the aggregate pollution as given. Using (2-13), (2-19) and (2-28), the pollution generated by consuming a brand with environmental quality $\lambda$ is given by:

$$z(\lambda) = \frac{\epsilon \rho L \tilde{\lambda}^{(y-a)(\sigma-1)} \lambda^{(\sigma-\gamma)-\alpha-\beta}}{1-G(\tilde{\lambda})} \tilde{\lambda}^{(y-a)(\sigma-1)} \lambda^{(\sigma-\gamma)-\alpha-\beta}$$  \hspace{1cm} (2-29)

When there are more varieties available in the market, the pollution generated by consuming a specific brand is smaller. Substituting (2-29) into (2-3), the aggregate pollution $Z$ can be expressed as

$$Z = \frac{L \epsilon \rho \tilde{\lambda}^{(y-a)(\sigma-1)}}{1-G(\tilde{\lambda})} \int_{\lambda}^{\tilde{\lambda}} \lambda^{(\sigma-1)-\gamma} g(\lambda) d\lambda$$  \hspace{1cm} (2-30)

Notice that the aggregate pollution is not directly affected by the number of firms. When there are more firms in the market, it will drive down the green price index and demand for every existing brand will be smaller. Consumers are buying more varieties while spending less on each variety and these two effects cancel out exactly.

Substituting (2-28) into (2-23) and using (2-10), (2-19) and (2-30), per-capita welfare is given by:

$$W = \frac{L^{1/(\sigma-1)} \left[1-G(\tilde{\lambda})\right]^{1/(\sigma-1)}}{1-G(\tilde{\lambda})} \left(\sigma \delta f_c\right)^{1/(\sigma-1)} \rho \tilde{\lambda}^{\alpha-\gamma} - \frac{L \epsilon \rho \tilde{\lambda}^{(y-a)(\sigma-1)}}{1-G(\tilde{\lambda})} \int_{\lambda}^{\tilde{\lambda}} \lambda^{(\sigma-1)-\gamma} g(\lambda) d\lambda$$  \hspace{1cm} (2-31)

Depending on the parameter values, per-capita welfare $W$ can be either positive or negative. A more stringent environmental standard affects per-capita welfare in several ways: first, a more stringent environmental standard makes it more difficult for
prospective entrants to enter the market successfully. There will be fewer firms producing at the steady-state equilibrium and the competition among all producing firms will be less intense. A representative consumer becomes worse off because she has to consume fewer varieties. Even though a representative consumer prefers products with better environmental quality, she has to pay a higher price for them, so aggregate consumption is smaller. Second, the effect of a more stringent environmental standard on aggregate pollution is unclear. When the environmental standard is higher, there are fewer varieties available and the average environmental quality is higher. However, consumers consume more of each variety. The pollution emissions generated from each variety are higher and, therefore, a higher standard may increase or decrease aggregate pollution. Overall, the effect of a more stringent environmental standard on per-capita welfare is ambiguous. The following proposition summarizes these results (see Algebraic Details for proof):

**Proposition 2-1:** A more stringent environmental standard \( \lambda \) will decrease aggregate consumption and may increase or decrease aggregate pollution. Therefore, the overall effect of raising the environmental standard \( \lambda \) on per-capita welfare is ambiguous.

In the case where a higher standard increases aggregate pollution, per-capita welfare is unambiguously decreasing in the standard and the optimal policy for the regulator would be to set the environmental standard as low as possible. However, if a higher standard decreases aggregate pollution, the effect of a higher environmental standard on per-capita welfare is ambiguous and an optimal standard may be obtained.
In the next section, we use a Pareto distribution to illustrate this possibility and the factors that affect the optimal standard are also discussed.

**Parameterization and the Optimal Standard**

To have a better understanding of the properties of the model, we assume that environmental quality levels are drawn from a Pareto distribution with scale parameter $b$ and shape parameter $k$ which is a commonly used distribution in the literature (see Helpman et al. (2004), Dinopoulos and Unel (2009)). In particular, we assume $(\alpha - \gamma)(\sigma - 1) < k < (\alpha + \beta)(\sigma - 1).$ Assuming that environmental quality levels follow a Pareto distribution is not essential in this paper. However, it makes the analysis more tractable.

With a Pareto distribution, the cumulative distribution is defined as: for $\lambda \geq b > 0$,

$$G(\lambda) = 1 - \left(\frac{b}{\lambda}\right)^k$$

(2-32)

The probability distribution function is then given by:

$$g(\lambda) = \frac{kb^k}{\lambda^{k+1}}$$

(2-33)

Using (2-33), the average environmental quality (2-20) can be written as:

$$\tilde{\lambda} = \left[\frac{k}{k - (\alpha - \gamma)(\sigma - 1)}\right]^{1/((\alpha - \gamma)(\sigma - 1))} \tilde{\lambda}$$

(2-34)

---

4 We assume that $k > (\alpha - \gamma)(\sigma - 1)$ to ensure the average environmental quality has a solution and is positive and we assume that $k < (\alpha + \beta)(\sigma - 1)$ to ensure the second order condition is satisfied.
It is clear that average environmental quality $\bar{\lambda}$ is an increasing function of the standard $\lambda$ as we have shown in lemma 1. Given the Pareto distribution and parameter values, this relationship becomes linear.

Using equations (2-28) and (2-32), the number of firms is given by:

$$M = \frac{L[1 - G(\bar{\lambda})]}{\sigma \delta f_e} = \frac{Lb^k \bar{\lambda}^{-k}}{\sigma \delta f_e} \quad (2-35)$$

Aggregate consumption is given by:

$$Q = \rho \left[ \frac{Lb^k}{\sigma \delta f_e [k - (\alpha - \gamma)(\sigma - 1)]} \right]^{-1} \bar{\lambda}^{-k/(\sigma - 1) + \alpha - \gamma} \quad (2-36)$$

Aggregate consumption is a decreasing function of the environmental standard as shown in proposition 2-1. When the environmental standard is more stringent, consumers enjoy fewer varieties, pay a higher average price and consume more of each variety.

Aggregate pollution is given by:

$$Z = L\varepsilon \rho \frac{k - (\alpha - \gamma)(\sigma - 1)}{k + \alpha + \beta - \sigma(\alpha - \gamma)} \bar{\lambda}^{-\beta - \gamma} \quad (2-37)$$

which is decreasing in the environmental standard.

Per-capita welfare is given by:

$$W = Q - Z = \rho \left[ \frac{Lb^k}{\sigma \delta f_e [k - (\alpha - \gamma)(\sigma - 1)]} \right]^{-1} \bar{\lambda}^{-k/(\sigma - 1) + \alpha - \gamma} - L\varepsilon \rho \frac{k - (\alpha - \gamma)(\sigma - 1)}{k + \alpha + \beta - \sigma(\alpha - \gamma)} \bar{\lambda}^{-\beta - \gamma} \quad (2-38)$$

Set $\frac{\partial W}{\partial \bar{\lambda}} = 0$, the optimal standard is given by
\[
\lambda^* = \left[ \frac{k + \alpha + \beta - \sigma(\alpha - \gamma)}{(\beta + \gamma)(\sigma - 1)eL} \right]^{\sigma - 1} \left[ \frac{L \delta f}{\sigma \delta f (k - (\alpha - \gamma)(\sigma - 1))} \right]^{1 - (\alpha + \beta)(\sigma - 1)}
\] 

(2-39)

**Proposition 2-2**: Given the Pareto distribution, there exists an optimal level of environmental standard to maximize welfare, that is given by equation (2-39).

Given any level of environmental standard, suppose the required environmental R&D increases. In order for any entrant to discover a new variety, firms must hire more R&D researchers. There will be fewer firms producing in the market and each firm’s revenue and profit will be higher at the steady-state equilibrium. Because more researchers are needed in order to discover a variety, fewer entrants will successfully enter the market and keep producing. The competition will be less intense and every firm will make more revenue and profit. Consumers will be worse off because there will be fewer varieties available at the steady-state equilibrium. An increase in environmental R&D, however will not affect aggregate pollution. There will be fewer firms producing at the steady-state equilibrium, but each firm will be producing more which generates more pollution. Overall, aggregate pollution will not change. An increase in environmental R&D will unambiguously decrease per-capita welfare. If the size of the economy is larger, aggregate expenditure will be higher and there will be more firms producing in the market. The size of the economy has several effects on per-capita welfare. Each consumer becomes better off because she consumes more varieties. But, she becomes worse off because as she spreads her expenditure (equal to her wage) among more varieties, consumption on each good becomes less. Third, with more firms producing and each firm producing the same amount of output as before, each consumer becomes worse off due to higher aggregate pollution. Overall,
the effect of bigger size of the economy on per-capita welfare is ambiguous depending on the value of the elasticity of substitution. If the elasticity of substitution is big enough (\( \sigma > 2 \)), the benefit from consuming more varieties will outweigh the negative utility caused by pollution. Per-capita welfare will increase in the size of the economy and the optimal standard will be higher. Otherwise, per-capita welfare will decrease in the size of the economy and the optimal standard will be lower. The following proposition summarizes these properties:

**Proposition 2-3**: If the required environmental R&D increases, it will be harder for potential entrants to enter the market successfully. Aggregate consumption will be lower and aggregate pollution will not be affected. Therefore, it will decrease per-capita welfare and increase the optimal standard; With a larger economy, aggregate consumption and aggregate pollution will be higher. Overall effect on per-capita welfare is ambiguous. If the elasticity of substitution is big enough, the optimal standard will increase in the size of the economy.

**Conclusions**

This chapter develops a model of heterogeneous firms to study the effect of a stricter environmental standard on firm's profitability, pollution and consumers' welfare. Firms in this model face C.E.S preferences and charge prices as a constant markup over their marginal costs which are positively related to the firm-specific environmental quality levels. We find that with a stricter standard, firms with low levels of environmental quality will exit and the competition will be less intense, successful firms earn higher revenues and profits. McManus and Kleinbaum (2009) find that increasing fuel economy standards 30% to 50% (35 MPG to 40.5 MPG) would increase the Detroit biggest three firms’ gross profits by roughly $3 billion per year. Although there will be
fewer firms in the market, each consumer consumes more of each variety. The effect of the standard on aggregate pollution is unclear. The overall effect on welfare is ambiguous depending on the relative importance of consumption and pollution to consumers.

**Algebraic Details**

In this section, we include the proofs and algebraic details for Chapter 2.

**Proof of Lemma 2-1:**

Since \( \lambda > \bar{\lambda} \), when \( \alpha > \gamma \), \( \lambda^{(\alpha-\gamma)(\sigma-1)} > \bar{\lambda}^{(\alpha-\gamma)(\sigma-1)} \). Substitute it into the integral expression of equation (2-20) to obtain

\[
\tilde{\lambda}^{(\alpha-\gamma)(\sigma-1)} = \frac{1}{1-G(\bar{\lambda})} \int_{x}^{\tilde{\lambda}} \tilde{\lambda}^{(\alpha-\gamma)(\sigma-1)} g(\tilde{\lambda}) d\tilde{\lambda} > \frac{1}{1-G(\bar{\lambda})} \int_{x}^{\bar{\lambda}} \bar{\lambda}^{(\alpha-\gamma)(\sigma-1)} g(\bar{\lambda}) d\bar{\lambda} = \bar{\lambda}^{(\alpha-\gamma)(\sigma-1)}
\]

which yields \( \tilde{\lambda} > \bar{\lambda} \). Similarly, when \( \alpha < \gamma \), we can also get \( \tilde{\lambda} > \bar{\lambda} \).

Let \( H(\bar{\lambda}) = \frac{1}{1-G(\bar{\lambda})} \int_{x}^{\bar{\lambda}} \bar{\lambda}^{(\alpha-\gamma)(\sigma-1)} g(\bar{\lambda}) d\bar{\lambda} \), differentiating equation (2-20) yields:

\[
\frac{\partial \tilde{\lambda}}{\partial \lambda} = \frac{1}{(\alpha-\gamma)(\sigma-1)} \left[ H(\bar{\lambda}) \right]^{1/((\alpha-\gamma)(\sigma-1))} \frac{\partial H}{\partial \lambda}
\]

where

\[
\frac{\partial H}{\partial \lambda} = \frac{-\tilde{\lambda}^{(\alpha-\gamma)(\sigma-1)} g(\tilde{\lambda}) \left[ 1-G(\tilde{\lambda}) \right] - \int_{x}^{\tilde{\lambda}} \tilde{\lambda}^{(\alpha-\gamma)(\sigma-1)} g(\tilde{\lambda}) d\tilde{\lambda} \left[ -g(\tilde{\lambda}) \right]}{\left[ 1-G(\tilde{\lambda}) \right]^{2}} = \frac{g(\bar{\lambda}) \left[ \tilde{\lambda}^{(\alpha-\gamma)(\sigma-1)} - \bar{\lambda}^{(\alpha-\gamma)(\sigma-1)} \right]}{1-G(\bar{\lambda})}.
\]

Since \( \tilde{\lambda} > \bar{\lambda} \), \( \frac{\partial H}{\partial \lambda} \) and \( \alpha - \gamma \) will have the same sign. Therefore, \( \frac{\partial \tilde{\lambda}}{\partial \lambda} > 0 \).
Proof of (2-23), (2-24) and (2-25):

Substitute (2-15) into aggregate revenue definition \( R = \int_0^\infty r(\lambda) M \mu(\lambda) d\lambda \), we can obtain
\[
R = \int_0^\infty r(\lambda) \frac{\lambda^{(\alpha-\gamma)(\sigma-1)}}{\lambda^{(\alpha-\gamma)(\sigma-1)}} M \mu(\lambda) d\lambda = Mr(\tilde{\lambda}) .
\]
Aggregate profit is defined as
\[
\Pi = \int_0^\infty \pi(\lambda) M \mu(\lambda) d\lambda , \text{ since } \pi(\lambda) = r(\lambda) / \sigma , \text{ } \Pi = \int_0^\infty r(\lambda) M \mu(\lambda) d\lambda / \sigma = Mr(\tilde{\lambda}) / \sigma = M \pi(\tilde{\lambda}) .
\]
Aggregate quantity is given by
\[
Q = \frac{M^{1/\rho}}{L} \left[ \int_0^\infty \left[ \frac{\lambda^a q(\lambda)}{L} \right] \mu(\lambda) d\lambda \right]^{1/\rho}, \text{ using (2-10) and (2-14)},
\]
\[
Q = M^{1/\rho} \tilde{\lambda}^a q(\tilde{\lambda}) / L = \rho M^{1/\lambda} \tilde{\lambda}^{a-\gamma} .
\]

Proof of Proposition 2-1

Aggregate consumption is given by:
\[
Q = M^{1/\rho} \tilde{\lambda}^a q(\tilde{\lambda}) / L = L^{1/(\sigma-1)} \left[ 1 - G(\tilde{\lambda}) \right]^{1/(\sigma-1)} (\sigma f_e)^{1/(\sigma-1)} \tilde{\lambda}^{a-\gamma} .
\]
Using the definition of \( \tilde{\lambda} \), which is given by (2-20), we can rewrite aggregate consumption as
\[
Q = \rho \left( \frac{L}{\sigma f_e} \right)^{1/(\sigma-1)} \left[ \int_{\tilde{\lambda}}^\infty \lambda^{(\alpha-\gamma)(\sigma-1)} g(\lambda) d\lambda \right]^{1/(\sigma-1)} .
\]
Differentiating this equation yields:
\[
\frac{dQ}{d\tilde{\lambda}} = \rho \left( \frac{L}{\sigma f_e} \right)^{1/(\sigma-1)} \frac{1}{(\sigma-1)} \left[ \int_{\tilde{\lambda}}^\infty \lambda^{(\alpha-\gamma)(\sigma-1)} g(\lambda) d\lambda \right]^{1/(\sigma-1)} \left( -\tilde{\lambda}^{(\alpha-\gamma)(\sigma-1)} g(\tilde{\lambda}) \right) < 0 .
\]

From (2-30), aggregate pollution can be rewritten as
\[
Z = \frac{\epsilon p L \left[ \int_{\tilde{\lambda}}^\infty \lambda^{(\alpha-\gamma)(\sigma-1)} g(\lambda) d\lambda \right]}{\int_{\tilde{\lambda}}^\infty \lambda^{(\alpha-\gamma)(\sigma-1)} g(\lambda) d\lambda} .
\]
Differentiating this equation yields:
\[
\frac{\partial Z}{\partial \lambda} = \varepsilon p Lg(\lambda) \left[ \frac{\lambda^{(\alpha-\gamma)\gamma(\sigma-1)} \int_{\lambda}^{\infty} \lambda^{(a-1)-\gamma(\sigma-1-\beta)} g(\lambda) d\lambda - \lambda^{(\alpha-\gamma)\gamma(\sigma-1-\beta)} \int_{\lambda}^{\infty} \lambda^{(a-1)-\gamma(\sigma-1)} g(\lambda) d\lambda}{\left( \int_{\lambda}^{\infty} \lambda^{(a-\gamma)\gamma(\sigma-1)} g(\lambda) d\lambda \right)^2} \right].
\]

Whether \( \frac{\partial Z}{\partial \lambda} \) is positive or negative depends on the values of parameters and the distribution.
CHAPTER 3
TRADE, POLLUTION AND ENVIRONMENTAL STANDARDS

Overview

This chapter extends the previous chapter, developing an international trade model with firm specific environmental quality heterogeneity.

The Model

We consider a global economy consisting of \( n + 1 \) identical countries with \( n \geq 1 \). Each country has only one industry with heterogeneous firms and labor is the only factor of production. In each country, the aggregate supply of labor, \( L \), is fixed and remains constant over time.

Consumers

Assume we have \( L \) consumers with identical preferences within a country. The preferences for a representative consumer are given by

\[
U = Q - Z \tag{3-1}
\]

where \( Q \) is the aggregate consumption over a continuum of products which is indexed by \( \omega \) and is defined as a C.E.S function

\[
Q = \left[ \int_{\omega \in \Omega} \left( \lambda(\omega)^\alpha \frac{q(\omega)}{L} \right)^\rho d\omega \right]^{1/\rho} \tag{3-2}
\]

where \( 0 < \rho < 1 \) so that the elasticity of substitution between any two products is \( \sigma = 1 / (1 - \rho) > 1 \). \( q(\omega) \) is the aggregate consumption of brand \( \omega \), \( \Omega \) is the set of varieties available to consumers in a typical country and \( \lambda(\omega) > 1 \) denotes the time-invariant environmental quality of brand \( \omega \). Values of environmental quality \( \lambda(\omega) \) depend on firms’ R&D ability. Motivated by the automobile industry, we can consider the
environmental quality as the fuel-efficiency of different models of vehicles, so the model with a higher level of environmental quality has better fuel economy, i.e., higher miles per gallon (MPG). If a firm develops an electronic vehicle, \( \lambda(\omega) \) is very large.\(^1\) \( \alpha > 0 \) is a parameter capturing the intensity of consumer's preference for the differentiated goods with some degree of environmental quality. According to a 2009 survey by the Consumer Reports National Research Center, the most important considerations for today's new-car buyers are fuel economy, quality, safety, price, and value. Many consumers are willing to pay higher prices and even submit to a waiting list to purchase environmentally friendly hybrid vehicles. Higher \( \alpha \) means a representative consumer has a higher preference for the differentiated goods given their environmental quality. When \( \alpha \) is approaching zero, it means that consumers do not care about environmental quality contained in a product at all.

The consumption of these products generates pollution. \( Z \) is defined as the total amount of pollution summed over all varieties consumed in a country:

\[
Z = \int_{\omega \in \Omega} z(\omega)d\omega
\]  

(3-3)

The amount of pollution generated from consuming brand \( \omega \) by all consumers is:

\[
z(\omega) = \varepsilon \lambda(\omega)^{-\beta} q(\omega)
\]  

(3-4)

where \( \beta > 0 \) is a parameter capturing the pollution intensity. Higher \( \beta \) means that given an environmental quality, consuming the same amount of one brand will generate less pollution. When \( \beta \) approaches infinity, there will be no pollution; when \( \beta \) approaches zero, the environmental quality does not affect pollution anymore. Pollution from

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\(^1\) Electronic vehicles generate other types of pollution that for simplicity we do not discuss.
consuming a brand becomes proportional to the quantity demanded. \( \varepsilon > 0 \) is a parameter capturing this relationship, indicating that consuming 1 unit of brand \( \omega \) generates \( \varepsilon \) units of pollution if \( \beta = 0 \). Given parameters \( \beta \) and \( \varepsilon \), if a brand \( \omega \) has a higher level of environmental quality, consuming one unit of this product will generate less pollution.

Consuming varieties with higher environmental quality increases consumer utility in two ways: first, a representative consumer has preferences for those goods; and second, consuming the same amount of goods with higher environmental quality generates less pollution.

The representative consumer assumes that her own behavior does not affect aggregate pollution, so she takes aggregate pollution as given. Maximize her utility (3-1) subject to a budget constraint:

\[
\int_{\omega \in \Omega} p(\omega) \frac{q(\omega)}{L} d\omega = E
\]  

where \( E \) is per-capita consumer expenditure summed over all varieties, \( L \) is the number of consumers in a typical (home or foreign) market, \( p(\omega) \) is the corresponding price of brand \( \omega \) and \( q(\omega) \) is the aggregate consumption for brand \( \omega \).

The aggregate consumption \( q(\omega) \) and the aggregate expenditure \( r(\omega) \) for a particular brand \( \omega \) are:

\[
q(\omega) = ELP^{\sigma - 1} p(\omega)^{-\sigma} \lambda(\omega)^{\sigma (\sigma - 1)}
\]  

\[
r(\omega) = p(\omega)q(\omega) = ELP^{\sigma - 1} p(\omega)^{1 - \sigma} \lambda(\omega)^{\sigma (\sigma - 1)}
\]

where the price index adjusted for environmental quality (the green price index) is defined as:
\[
\begin{align*}
P &= \left[ \int_{\omega \in \Omega} \left( \frac{p(\omega)}{\lambda(\omega)^2} \right)^{1-\sigma} d\omega \right]^{\frac{1}{1-\sigma}} 
\end{align*}
\]

(3-8)

When consumers do not have any preference for the environmentally friendly products, \( \alpha = 0 \), the green price index collapses to the standard aggregate price index as shown in Melitz (2003). The aggregate consumption and the optimal expenditure for brand \( \omega \) both increase in aggregate consumer expenditure \( EL \), the green price index \( P \) and its level of environmental quality \( \lambda(\omega) \); both decrease in its own price \( p(\omega) \).

**Firms**

Labor is the only factor of production, with each worker supplying one unit of labor, so the labor supply is given by the number of consumers, \( L \). There is a continuum of firms and each firm chooses to produce a different variety. Initially, in a typical market, the regulator sets an environmental standard \( \bar{\lambda} \) and firms have to invest in environmental R&D before they start producing. In order for any firm to begin producing a variety, it will first invest a fixed entry cost \( f_e > 0 \), that is measured in units of labor and is interpreted as the number of R&D researchers required by the entrant to discover a new variety. All firms pay the same entry cost \( f_e \) but will discover varieties with different environmental quality. We interpret this fixed entry cost as environmental R&D. After incurring environmental R&D, firms draw their environmental quality parameter, \( \lambda \), out of a commonly known distribution. This process captures the uncertainty of environmental R&D. For any producing firm, assume the marginal cost is an increasing function of environmental quality: \( MC = \lambda' \). Further, assume that there is no fixed production cost once the variety has been discovered. Therefore, in order to produce \( q \)
units of output, \( l = \lambda^\gamma q \) units of labor are required. Because marginal cost increases in environmental quality, it will cost more for those firms with higher environmental qualities. For the remainder of this chapter, products are labeled based on their environmental quality levels because each brand is associated with a unique environmental quality level.

Firms have the choice whether to incur fixed trade costs \( f_x > 0 \) and Iceberg per-unit trade costs \( \tau > 1 \) in order to export. Neither of these costs depend on a firm’s environmental quality level. Iceberg trade costs are modeled as \( \tau > 1 \) units of output must be produced at home in order for one unit to arrive at a foreign country. Firms make the export decision after they learn their environmental quality levels.

Regardless of the differences in environmental quality, each firm faces a residual demand curve with constant elasticity because of the C.E.S consumption index. The producing firms maximize their profits by taking the number of varieties and the green price index \( P \) as given. A firm with environmental quality \( \lambda \) will set its domestic profit-maximizing price as a constant markup over its marginal cost

\[
p(\lambda) = \frac{\lambda^\gamma}{\rho}
\]

where we normalize the wage rate to one \( (w = 1) \) and \( p_d(\lambda) \) is the consumer price prevailing in the domestic market. An exporting firm will set a higher price in the foreign market due to the Iceberg trade cost and the consumer price prevailing in the foreign market \( p_x(\lambda) \) is given by

\[
p_x(\lambda) = \frac{\tau \lambda^\gamma}{\rho}
\]
A firm with environmental quality \( \lambda \) will sell \( q_d(\lambda) \) amount in the domestic market and if it decides to export, it will sell \( q_x(\lambda) \) amount in each of \( n \) foreign markets:

\[
q_d(\lambda) = ELP^{\sigma-1} \rho^{\sigma} \lambda^{(\sigma-1)\gamma} \tag{3-11}
\]

and,

\[
q_x(\lambda) = \tau^{-\sigma} ELP^{\sigma-1} \rho^{\sigma} \lambda^{(\sigma-1)\gamma} \tag{3-12}
\]

Therefore, the combined production of a firm, \( q(\lambda) \), depends on its export status:

If the firm does not export,

\[
q(\lambda) = q_d(\lambda) \tag{3-13}
\]

If the firm exports to all \( n \) foreign countries,

\[
q(\lambda) = q_d(\lambda) + nq_x(\lambda) = (1 + n\tau^{-\sigma})q_d(\lambda) = (1 + n\tau^{-\sigma})ELP^{\sigma-1} \rho^{\sigma} \lambda^{(\sigma-1)\gamma} \tag{3-14}
\]

Respectively, the revenues earned from domestic sales \( r_d(\lambda) \) and sales in each of \( n \) export markets \( r_x(\lambda) \) are given by

\[
r_d(\lambda) = EL(P\rho)^{\sigma-1} \lambda^{(\sigma-1)\gamma} \tag{3-15}
\]

and

\[
r_x(\lambda) = \tau^{1-\sigma} r_d(\lambda) = \tau^{1-\sigma} EL(P\rho)^{\sigma-1} \lambda^{(\sigma-1)\gamma} \tag{3-16}
\]

Therefore, the combined revenue, \( r(\lambda) \), also depends on its export status:

If the firm does not export,

\[
r(\lambda) = r_d(\lambda) = EL(P\rho)^{\sigma-1} \lambda^{(\sigma-1)\gamma} \tag{3-17}
\]

If the firm exports to all \( n \) foreign countries,

\[
r(\lambda) = r_d(\lambda) + nr_x(\lambda) = (1 + n\tau^{1-\sigma})r_d(\lambda) = (1 + n\tau^{1-\sigma})EL(P\rho)^{\sigma-1} \lambda^{(\sigma-1)\gamma} \tag{3-18}
\]
Similarly, the profits of any exporting firms in each period can be decomposed into two parts: profits earned from domestic sales $\pi_d(\lambda)$ and profits earned from sales in each of $n$ export markets $\pi_x(\lambda)$.

$$\pi_d(\lambda) = \frac{r_d(\lambda)}{\sigma}$$

(3-19)

and

$$\pi_x(\lambda) = \frac{r_x(\lambda)}{\sigma} - f_x$$

(3-20)

A firm with environmental quality $\lambda$ that produces for its domestic market exports to all $n$ countries if $\pi_x(\lambda) \geq 0$. No firm will ever export and not produce for its domestic market since the domestic profit, $\pi_d(\lambda)$, is always positive as long as it meets the current environmental standard. Therefore, a firm with environmental quality $\lambda$ earns a combined per-period profit $\pi(\lambda)$, that is given by:

$$\pi(\lambda) = \pi_d(\lambda) + \max \{0, n\pi_x(\lambda)\}$$

(3-21)

The total pollution generated from a firm with an environmental quality $\lambda$, $z(\lambda)$, depends on its export status:

If the firm does not export,

$$z(\lambda) = eELP^{\sigma-1}\rho^\sigma \lambda^{a(\sigma-1)-\gamma-\beta}$$

(3-22)

If the firm exports to all $n$ foreign countries,

$$z(\lambda) = z_d(\lambda) + nz_x(\lambda) = (1 + n\tau^{-\sigma})z_d(\lambda) = (1 + n\tau^{-\sigma})eELP^{\sigma-1}\rho^\sigma \lambda^{a(\sigma-1)-\gamma-\beta}$$

(3-23)

**Entry Decisions**

Every country sets an environmental standard $\bar{\lambda}$ ($\bar{\lambda} > 1$). This regulated level is strictly enforced so any firm producing a variety with $\lambda < \bar{\lambda}$ will not be able to sell its
products at all in either domestic or foreign markets. Suppose that in each country, there are a large number of prospective ex-ante identical entrants. Initially, a firm incurs the fixed entry cost, the environmental R&D, $f_e$, then it draws its environmental quality parameter $\lambda$ from a common and known distribution $g(\lambda)$ with positive support over $(0, \infty)$ and with continuous cumulative distribution $G(\lambda)$. The properties of $g(\lambda)$ determine the benefits of entry measured by the relevant expected discounted profits. After observing its environmental quality level $\lambda$, a firm decides whether to exit the market immediately or start producing. If a firm discovers a product with low environmental quality $\lambda < \bar{\lambda}$, it does not meet the current environmental standard and will immediately exit and not produce. If a firm discovers a product with environmental quality equal to or greater than the standard $\lambda \geq \bar{\lambda}$, it will enter the market and make positive profits. Any producing firm which meets the current environmental standard is always earning positive profits in the domestic market without the fixed production cost because of the constant markup over marginal cost due to the C.E.S structure. Also, after observing its environmental quality level $\lambda$, a firm decides whether to incur the fixed export cost $f_x$ to sell its products to foreign markets. A firm with environmental quality $\lambda$ produces for its domestic market exports to all $n$ foreign countries, only if $\pi_x(\lambda) \geq 0$. Assume that consumers have a strong preference for products with better environmental quality, $\alpha > \gamma$. In this case, higher demand for environmentally friendly products compensates for the fact that it costs firms more to produce these products. A firm with a higher environmental quality level $\lambda$, earns higher revenue because it is able to charge a higher price and make higher profits. $\pi_x(\lambda)$ increases monotonically in $\lambda$. 
Denote \( \lambda_x \) as the cutoff environmental quality level for exporting firms, where

\[
\pi_x(\lambda_x) = r_x(\lambda_x) / \sigma - f_x = 0 \quad (3-24)
\]

**Proposition 3-1**: As long as the fixed export cost \( f_x \) is greater than

\[
L(\beta)^{\sigma-1} \lambda^{(\alpha-\gamma)/(\sigma-1)} ,
\]

there will be some firms that will export while some firms will only serve the domestic market.

The fixed export cost \( f_x \) has to be greater than \( L(\beta)^{\sigma-1} \lambda^{(\alpha-\gamma)/(\sigma-1)} \) to ensure that the cutoff environmental quality meets the standard. In the absence of the fixed export cost \( (f_x = 0) \), all firms who survive in the domestic market will export to foreign markets as well.

Each incumbent firm faces a constant probability of death \( \delta \) in each period as a result of being hit by a stochastic shock \( (0 < \delta < 1) \). In the present context, this stochastic shock can be interpreted as changing tastes that eliminate the demand for a particular variety. Since the exit is uncorrelated with the environmental quality, the exit process will not affect the equilibrium environmental quality distribution \( \mu(\lambda) \). As in Melitz (2003), the ex-ante probability of drawing an environmental quality level \( \lambda \) is governed by the density function \( g(\lambda) \) and the ex-ante probability of successful entry \( p_{\text{in}} = 1 - G(\lambda) \). The equilibrium distribution of environmental quality \( \mu(\lambda) \) is then determined by initial draw, conditional on successful entry \( p_{\text{in}} = 1 - G(\lambda) \). Therefore, \( \mu(\lambda) \) is the conditional distribution of \( g(\lambda) \) on the interval \( [\lambda, \infty) \):

\[
\mu(\lambda) = \frac{g(\lambda)}{1 - G(\lambda)} \quad (3-25)
\]
Suppose the regulator decided to set a higher environmental standard, it would change the equilibrium distribution of environmental quality $\mu(\lambda)$. It would be harder for any potential firm to enter the market, the ex-ante probability of successful entry would be smaller and the equilibrium distribution would be bigger.

The ex-ante probability that an incumbent firm will export is given by

$$p_x = \frac{1 - G(\lambda_x)}{1 - G(\lambda)}$$

(3-26)

This probability is also the ex-post fraction of firms that export.

**Aggregation**

Let $M_p$ denote the number of varieties produced in any country and $M_x$ be the number of varieties that each country exports. $M_x$ is given by:

$$M_x = p_x M_p$$

(3-27)

Then, the total number of varieties available for consumption in any country is given by:

$$M_c = M_p + nM_x = (1 + np_x)M_p$$

(3-28)

Let $\tilde{\lambda}_p$ denote the weighted average of the environmental quality levels of all domestically produced goods:

$$\tilde{\lambda}_p = \tilde{\lambda}(\tilde{\lambda}) = \left[ \frac{1}{1 - G(\lambda)} \int_{\lambda}^{\infty} \lambda^{(\alpha - \gamma)(\sigma - 1)} g(\lambda) d\lambda \right]^{1/(\alpha - \gamma)(\sigma - 1)}$$

(3-29)

$\tilde{\lambda}_p$ is a weighted average of the environmental quality levels of all domestic firms and can be interpreted as the expected environmental quality level. The environmental standard $\tilde{\lambda}$ and the ex-ante distribution $g(\lambda)$ will determine the average environmental quality $\tilde{\lambda}_p$ in equilibrium.
Let \( \tilde{\lambda}_x \) denote the weighted average environmental quality level of exporting firms:

\[
\tilde{\lambda}_x = \tilde{\lambda}(\lambda_x) = \left[ \frac{1}{1-G(\lambda_x)} \int_0^{\infty} \lambda^{(a-\gamma)(\sigma-1)} g(\lambda) d\lambda \right]^{\frac{1}{(a-\gamma)(\sigma-1)}}
\]

(3-30)

The combined average environmental quality of all goods, \( \tilde{\lambda}_c \), is given by:

\[
\tilde{\lambda}_c = \left[ \frac{M_p}{M_c} \tilde{\lambda}_p^{(a-\gamma)(\sigma-1)} + \frac{M_x}{M_c} \left( r^{-1} \tilde{\lambda}_x^{(a-\gamma)(\sigma-1)} \right)^{\frac{1}{(a-\gamma)(\sigma-1)}} \right]
\]

(3-31)

\( \tilde{\lambda}_c \) is the weighted average environmental quality level of all varieties from both domestic and foreign firms competing in one country.

Because any firm that does not meet the environmental standard is not able to enter the market at all, the standard level is the minimum environmental quality level of all producing firms and it will be lower than the average environmental quality level of all firms. Furthermore, an increase of the standard forces firms with low environmental quality levels to exit the market, that in turn increases the average environmental quality level of all produced varieties. Similarly, the export environmental quality cutoff level is the minimum environmental quality level of all exporting firms and it will be lower than the average environmental quality level of all exporting firms. An increase of the cutoff level forces firms with low environmental quality levels to only serve the domestic market. Therefore, the average environmental quality level of all exporting firms also increases. The following lemma summarizes these properties. (See Algebraic Details for proof).

**Lemma 3-1:** The average environmental quality level of all produced varieties in an economy is strictly greater and increases in the environmental standard, i.e., \( \tilde{\lambda}_p > \tilde{\lambda}_c \).
and \( \frac{\partial \tilde{\lambda}_p}{\partial \tilde{\lambda}} > 0 \). The average environmental quality level of all exporting firms is strictly greater and increases in the export cutoff environmental quality level, i.e., \( \tilde{\lambda}_x > \lambda_x \) and \( \frac{\partial \tilde{\lambda}_x}{\partial \lambda_x} > 0 \).

The green price index \( P \), expenditure level \( R \) and aggregate quantity \( Q \) in any country can then be written as functions of only the average level of environmental quality \( \tilde{\lambda}_c \) and the number of varieties consumed \( M_c \) (See Algebraic Details):

\[
P = M_c^{1/(1-\sigma)} \tilde{\lambda}_c^{\gamma-\sigma} / \rho
\]
\[P = M_c^{1/(1-\sigma)} \tilde{\lambda}_c^{\gamma-\sigma} / \rho \tag{3-32}\]

\[
R = M_c r_d(\tilde{\lambda}_c)
\]
\[R = M_c r_d(\tilde{\lambda}_c) \tag{3-33}\]

\[
Q = \rho M_c^{1/(\sigma-1)} \tilde{\lambda}_c^{\sigma-\gamma}
\]
\[Q = \rho M_c^{1/(\sigma-1)} \tilde{\lambda}_c^{\sigma-\gamma} \tag{3-34}\]

The aggregate equilibrium in any country is identical to one with \( M_c \) representative firms that have the same environmental quality \( \tilde{\lambda}_c \).

The overall average revenue, \( \bar{r} \), and profit, \( \bar{\pi} \), from both domestic and foreign markets are given by:

\[
\bar{r} = r_d(\tilde{\lambda}_p) + p_x n r_d(\tilde{\lambda}_x)
\]
\[\bar{r} = r_d(\tilde{\lambda}_p) + p_x n r_d(\tilde{\lambda}_x) \tag{3-35}\]

and

\[
\bar{\pi} = \pi_d(\tilde{\lambda}_p) + p_x n \pi_d(\tilde{\lambda}_x)
\]
\[\bar{\pi} = \pi_d(\tilde{\lambda}_p) + p_x n \pi_d(\tilde{\lambda}_x) \tag{3-36}\]

**Free Entry and the Value of the Firms**

A firm producing a variety with environmental quality level \( \lambda \) earns a per period profit \( \pi(\lambda) \). Because each firm faces a constant probability of death \( \delta \) in each period, the market value of a firm with an environmental quality level \( \lambda \) is given by:
\( v(\lambda) = \max \left\{ 0, \sum_{t=0}^{\infty} (1 - \delta)^t \pi(\lambda) \right\} = \max \left\{ 0, -\frac{\pi(\lambda)}{\delta} \right\} \) 

(3-37)

where the second equality follows from the fact that the environmental quality contained in each firm's product remains constant during its lifetime, so that every period it earns the same profit. Because the probability of successful entry is \( 1 - G(\lambda) \), the net benefits of entering the domestic market are equal to the expected value of a firm \( 1 - G(\lambda) \nu \), where \( \nu = \pi(\lambda) / \delta \) is the ex-ante value of a prospective entrant and \( \pi \) is defined by \( \pi = \pi_d(\lambda) + p_n \pi_n(\lambda) \). Setting the benefits of entry equal to the fixed R&D costs yields the free entry condition:

\( \bar{\pi} = \frac{\delta f_e}{1 - G(\lambda)} \) 

(3-38)

The average profit \( \bar{\pi} \) is solely determined by the probability of death \( \delta \), the fixed environmental R&D \( f_e \) and the environmental standard \( \lambda \). Given the probability of death \( \delta \) and the fixed environmental R&D \( f_e \), if regulators set higher standards prospective firms are less likely to enter successfully, an entrant would expect there will be less firms in the markets and its expected value would be higher.

**Steady-State Equilibrium**

At the steady-state equilibrium, the zero cutoff profit condition will determine the relationship between the average profit per firm \( \bar{\pi} \) and the export cutoff environmental quality level \( \lambda_x \).

Combine (3-15) and (3-19), we have

\[
\frac{\pi_d(\lambda_p)}{\pi_d(\lambda_x)} = \frac{r_d(\lambda_p)}{r_d(\lambda_x)} = \left( \frac{\lambda_p}{\lambda_x} \right)^{(\alpha - \gamma)/(\sigma - 1)}
\]

(3-39)
From (3-16), we have

\[
\frac{r_x(\tilde{\lambda}_x)}{r_x(\lambda)} = \left( \frac{\tilde{\lambda}_x}{\lambda_x} \right)^{(a-\gamma)(\sigma-1)}
\]  

(3-40)

Using (3-20), (3-24), (3-39) and (3-40), the overall average profit from both domestic and foreign markets (3-36) becomes

\[
\bar{\pi} = \tau^{\sigma-1} f_x \left( \frac{\tilde{\lambda}_p}{\tilde{\lambda}_x} \right)^{(a-\gamma)(\sigma-1)} + p_x nf_x \left[ \left( \frac{\tilde{\lambda}_x}{\lambda_x} \right)^{(a-\gamma)(\sigma-1)} - 1 \right]
\]  

(3-41)

where \( p_x \) and \( \tilde{\lambda}_x \) are both functions of \( \lambda_x \). Therefore, equation (3-41) identifies the new zero cutoff profit condition for the open economy.

At the steady-state equilibrium, given environmental standard \( \tilde{\lambda} \) from the free entry condition (3-38), the overall average profit can be identified. Together with the new zero cutoff profit condition, a unique cutoff environmental quality level \( \lambda_x \) can be identified. This equilibrium cutoff environmental quality level \( \lambda_x \) and the standard \( \tilde{\lambda} \) determine the average environmental quality level of exporting firms \( \tilde{\lambda}_x \), the average environmental quality level of all domestically produced goods \( \tilde{\lambda}_p \), and the combined average of all goods \( \tilde{\lambda}_c \). The ex-ante successful entry and export probabilities \( p_{in} \) and \( p_x \) are determined as well.

The average revenue (3-35) is then determined by the zero cutoff profit condition (3-41) and the free entry condition (3-38): (See Algebraic Details)

\[
\bar{r} = \sigma(\bar{\pi} + p_x nf_x)
\]  

(3-42)

At the steady-state equilibrium, the aggregate variables must remain constant over time, so the number of firms is constant. Therefore in any single period, the number of
successful entrants $p_{in}M_e$ must be equal to the number of incumbent firms who are forced to exit the market due to a bad shock, i.e., $p_{in}M_e = \delta M_p$, where $M_e$ is the number of potential entrants and $p_{in}M_e$ is the number of firms who successfully enter the market. Since the entering and exiting firms have the same distribution of environmental quality levels, at the steady-state equilibrium, the distribution of environmental quality $\mu(\lambda)$ is not affected by this simultaneous entry and exit. The labor employed by the prospective entrants for environmental R&D to discover the varieties and the labor employed by the incumbent firms for manufacturing are denoted by $L_e$ and $L_m$. For the full employment condition to be satisfied, labor demand equals labor supply, i.e., $L_e + L_m = L$. Total payments to workers in manufacturing are equal to the difference between aggregate revenue and profit: $L_m = R - \Pi$. The labor employed by the prospective entrants for environmental R&D to discover the varieties is given by $L_e = M_e f_e$. Using the aggregate stability condition, $p_{in}M_e = \delta M_p$, and the free entry condition, $\bar{\rho} = \frac{\delta f_e}{1 - G(\lambda)}$, $L_e$ can be written as:

$$L_e = M_e f_e = \frac{\delta M_p}{1 - G(\lambda)} f_e = M_p \bar{\rho} = \Pi$$

(3-43)

Thus, the aggregate amount of labor employed by the prospective entrants for environmental R&D equals the level of aggregate profits earned by all producers in a typical market. Also, the aggregate revenue $R = EL = L_m + \Pi = L_m + L_e$ must also equal the total payments to labor $L$ and is solely determined by the total number of consumers. Per-capita expenditure equals unity due to the choice of labor as the numeraire, i.e., $E = w \equiv 1$ and the aggregate revenue $R = L$. Using (3-38) and (3-42), the
number of producing firms in any period can then be determined from the average profit:

\[
M_p = \frac{EL}{\bar{F}} = \frac{L}{\sigma(\bar{E} + p_n\sigma f)} = \frac{L}{\sigma[f_\delta + 1-G(\lambda)]nf_x}
\]  

(3-44)

At the steady-state equilibrium, the number of varieties produced domestically is determined by the size of the economy, the elasticity of substitution between any two products, the stochastic shock, environmental R&D and the environmental standard.

Substituting (3-44) into (3-28) yields the total number of varieties that are available for consumption:

\[
M_c = (1 + np_x)M_p = \frac{L}{\sigma[f_\delta + 1-G(\lambda)]nf_x}
\]  

(3-45)

Notice that in the absence of trade \((n = 0)\), the number of varieties produced equals the number of varieties consumed, i.e., \(M_p = M_c\).

**Pollution and Welfare**

Both consumers and producers take aggregate pollution as given. Aggregate pollution \(Z\) can be expressed as

\[
Z = \frac{\varepsilon pL}{\lambda_c^{(a-\gamma)(\sigma-1)}} \left[ M_p \int_x^{\infty} \lambda^{a(\sigma-1)-\gamma-\beta} \mu(\lambda)d\lambda + \frac{n}{\tau^\alpha} \int_x^{\infty} \lambda^{a(\sigma-1)-\gamma-\beta} \mu(\lambda)d\lambda \right]
\]  

(3-38)

Per-capita welfare is given by:

\[
W = \left( \frac{L}{\sigma f_x} \right)^{1/(\sigma-1)} \frac{\rho\lambda_c^{a-\gamma}}{\tau} \left[ \frac{M_p}{M_c} \int_x^{\infty} \lambda^{a(\sigma-1)-\gamma-\beta} \mu(\lambda)d\lambda + \frac{n}{\tau^\alpha} \frac{M_x}{M_c} \int_x^{\infty} \lambda^{a(\sigma-1)-\gamma-\beta} \mu(\lambda)d\lambda \right]
\]  

(3-39)

Depending on the parameter values, per-capita welfare \(W\) can be either positive or negative. A more stringent environmental standard affects per-capita welfare in
several ways: First, a more stringent environmental standard makes it more difficult for prospective entrants to enter the market successfully and firms that cannot meet the new standard will have to exit the market. There will be fewer domestic firms producing at the steady-state equilibrium and consumers will enjoy more varieties of imported goods. However, the total number of varieties that are available for consumption is not clear depending on the trade costs. For example, if the fixed trade cost is small ($f_x < \frac{\delta f_c}{1 - G(\bar{x})}$), there are more foreign firms that are able to export their products and domestic consumers will have more varieties to consume. However, when there are more varieties available in a typical market, the green price index is driven down and there is lower demand for every brand. Consumers are buying more varieties while spending less on each variety and these two effects cancel out exactly. Similar logic applies when there are fewer varieties. Therefore, the number of varieties does not affect aggregate consumption directly. A stricter environmental standard drives down the cutoff environmental quality level for exporting firms and the average environmental quality level is lower. Because consumers prefer products with better environmental quality, aggregate consumption is smaller. Second, the effect of a more stringent environmental standard on aggregate pollution is unclear. When the environmental standard is higher, if there are fewer varieties available, the average environmental quality is higher and consumers consume more of each variety. The pollution emission generated from each variety is higher and, therefore, a higher standard may increase or decrease aggregate pollution. Overall, the effect of a more stringent environmental standard on per-capita welfare is ambiguous. The following proposition summarizes these results:
Proposition 3-2: A more stringent environmental standard $\bar{\lambda}$ will decrease the export cutoff environmental quality level $\lambda_x$, decrease aggregate consumption and may increase or decrease aggregate pollution. Therefore, the overall effect of raising the environmental standard $\bar{\lambda}$ on the per-capita welfare is ambiguous. (See Figure 3-1.)

The Impact of International Trade

Trade liberalization is measured by an increase in the number of trading partners $n$, a reduction in foreign entry cost $f_x$, or a reduction in per-unit trade costs $\tau$. The effects of trade liberalization are transmitted through changes in the export cutoff environmental quality level $\lambda_x$ as described in Lemma 3-2. (See Algebraic Details for proof.)

Lemma 3-2: An increase in the number of trading partners $(n \uparrow)$ increases the export cutoff environmental quality level $\lambda_x$; whereas a reduction in foreign entry cost $(f_x \downarrow)$ or a reduction in per-unit trade costs $(\tau \downarrow)$ decreases $\lambda_x$ (i.e., $d\lambda_x / dn > 0$, $d\lambda_x / df_x > 0$, and $d\lambda_x / d\tau > 0$).

For any given environmental standard $\bar{\lambda}$, the export cutoff environmental quality level $\lambda_x$, the total number of varieties available for consumption $M_x$ and the ex-ante expected profit $\bar{\pi}$ are fixed. Any form of trade liberalization does not change the ex-ante profits (given by equation (3-38)). An increase in the number of trading partners $(n \uparrow)$ increases the number of available varieties $M_x$. Because there are more firms competing in the market, it reduces the profits of the marginal exporter, and the cutoff environmental quality level $\lambda_x$ has to increase to restore profits back to the equilibrium level.
A reduction in foreign entry cost \((f_x \downarrow)\) or a reduction in per-unit trade costs \((\tau \downarrow)\) has two effects: First, it makes firms more likely to export to foreign markets because it increases profits from exports and the cutoff environmental quality level \(\lambda_x\) has to decrease to restore profits back to the equilibrium level. Second, the increased competition tends to reduce profits and requires an increase in the cutoff environmental quality level \(\lambda_x\). The first effect dominates, therefore, lower trade costs generate lower cutoff environmental quality level \(\lambda_x\).

The following proposition discusses the effects of trade liberalization on aggregate consumption, pollution and the per-capita welfare. (See Algebraic Details for proof.)

**Proposition 3-3:** Trade liberalization increases aggregate consumption (i.e., \(\frac{dQ}{dn} > 0\), \(\frac{dQ}{df_x} < 0\), and \(\frac{dQ}{d\tau} < 0\)) and may increase or decrease aggregate pollution. Therefore, the overall effect of trade liberalization on the per-capita welfare is ambiguous.

**Conclusions**

This chapter builds a simple monopolistic competition model of firm heterogeneity and international trade. Firms in this model face C.E.S preferences and charge prices as a constant markup over their marginal costs that are positively related to the firm-specific environmental quality levels. It studies the effect of a stricter environmental standard on firms' profitability, pollution and consumers' welfare when countries are allowed to trade. I find that with a stricter standard, firms with low levels of environmental quality will exit the market. However, in order to restore the steady-state equilibrium condition, more firms are able to export to foreign markets. Firms are making higher revenues and profits than before, despite their exporting status. The
effect of the standard on aggregate pollution is unclear. The overall effect on welfare is ambiguous depending on the relative importance of consumption and pollution to consumers. The impacts of trade liberalization are also studies. Trade liberalization changes the cutoff environmental quality. Firms who only serve the domestic market make lower revenues and profits; firms who are able to export now increase their sales to foreign countries, make up their loss of domestic sales and overall revenues are higher. Trade liberalization ultimately increases the aggregate consumption. Unfortunately, it is hard to tell whether trade liberalization increases or decreases the aggregate pollution.

Algebraic Details

In this section, we include the proofs and algebraic details for Chapter 3.

Proof of Lemma 3-1:

Since every producing firm has to meet the environmental standard, \( \lambda > \lambda_c \), we have \( \bar{\lambda}_{(\alpha - \gamma)(\sigma - 1)} > \lambda_{(\alpha - \gamma)(\sigma - 1)} \). Substitute into the definition of \( \bar{\lambda}_p \), which is given by equation (3-29), to obtain

\[
\bar{\lambda}_p^{(\alpha - \gamma)(\sigma - 1)} = \frac{1}{1 - G(\bar{\lambda})} \int_{\bar{\lambda}}^{\infty} \lambda^{(\alpha - \gamma)(\sigma - 1)} g(\lambda) d\lambda > \frac{1}{1 - G(\bar{\lambda})} \int_{\lambda}^{\infty} \lambda^{(\alpha - \gamma)(\sigma - 1)} g(\lambda) d\lambda = \bar{\lambda}_{(\alpha - \gamma)(\sigma - 1)}
\]

which yields \( \bar{\lambda}_p > \bar{\lambda} \).

Let \( H(\bar{\lambda}) = \frac{1}{1 - G(\bar{\lambda})} \int_{\bar{\lambda}}^{\infty} \lambda^{(\alpha - \gamma)(\sigma - 1)} g(\lambda) d\lambda \), differentiation of equation (3-29) yields:

\[
\frac{\partial \bar{\lambda}}{\partial \bar{\lambda}} = \frac{1}{(\alpha - \gamma)(\sigma - 1)} \left[ H(\bar{\lambda}) \right]^{1/(\alpha - \gamma)(\sigma - 1)} \frac{\partial H}{\partial \bar{\lambda}}
\]
where
\[
\frac{\partial H}{\partial \lambda} = -\lambda^{(\alpha - \gamma)(\sigma - 1)} g(\lambda) \left[ 1 - G(\lambda) \right] - \int_{\lambda_p}^{\lambda_x} \lambda^{(\alpha - \gamma)(\sigma - 1)} g(\lambda)d\lambda \left[ -g(\lambda) \right] = \frac{g(\lambda) \left[ \lambda^{(\alpha - \gamma)(\sigma - 1)} - \lambda^{(\alpha - \gamma)(\sigma - 1)} \right]}{1 - G(\lambda)}.
\]

Since \( \lambda_p > \lambda \), \( \frac{\partial H}{\partial \lambda} > 0 \). Therefore, \( \frac{\partial \lambda_p}{\partial \lambda} > 0 \).

\( \hat{\lambda}_x \) is the weighted average environmental quality level of all exporting firms and is given by equation (3-30). \( \hat{\lambda}_x \) is the cutoff environmental quality level, so for every exporting firm, its environmental quality level has to be higher, \( \lambda > \hat{\lambda}_x \). We have
\( \lambda^{(\alpha - \gamma)(\sigma - 1)} > \hat{\lambda}_x^{(\alpha - \gamma)(\sigma - 1)} \). Substitute into equation (3-30) to obtain
\[
\hat{\lambda}_x^{(\alpha - \gamma)(\sigma - 1)} = \frac{1}{1 - G(\lambda_x)} \int_{\lambda_x}^{\lambda_p} \lambda^{(\alpha - \gamma)(\sigma - 1)} g(\lambda)d\lambda + \frac{1}{1 - G(\lambda_x)} \int_{\lambda_x}^{\lambda_x} \lambda^{(\alpha - \gamma)(\sigma - 1)} g(\lambda)d\lambda = \lambda_x^{(\alpha - \gamma)(\sigma - 1)}
\]
which yields \( \hat{\lambda}_x > \lambda_x \).

Let \( J(\lambda_x) = \frac{1}{1 - G(\lambda_x)} \int_{\lambda_x}^{\lambda_p} \lambda^{(\alpha - \gamma)(\sigma - 1)} g(\lambda)d\lambda \), differentiation of equation (3-30) yields:
\[
\frac{\partial \hat{\lambda}_x}{\partial \lambda_x} = \frac{1}{(\alpha - \gamma)(\sigma - 1)} \left[ J(\lambda_x) \right]^{(\alpha - \gamma)(\sigma - 1)} \frac{\partial J}{\partial \lambda_x}
\]
where
\[
\frac{\partial J}{\partial \lambda_x} = -\lambda_x^{(\alpha - \gamma)(\sigma - 1)} g(\lambda_x) \left[ 1 - G(\lambda_x) \right] - \int_{\lambda_x}^{\lambda_p} \lambda^{(\alpha - \gamma)(\sigma - 1)} g(\lambda)d\lambda \left[ -g(\lambda_x) \right] = \frac{g(\lambda_x) \left[ \lambda_x^{(\alpha - \gamma)(\sigma - 1)} - \lambda_x^{(\alpha - \gamma)(\sigma - 1)} \right]}{1 - G(\lambda_x)}.
\]

Since \( \hat{\lambda}_x > \lambda_x \), \( \frac{\partial J}{\partial \lambda_x} > 0 \). Therefore, \( \frac{\partial \hat{\lambda}_x}{\partial \lambda_x} > 0 \).
Proof of the aggregate variables (3-32), (3-33) and (3-34):

Using (3-9) and (3-10), the green price index \( P \) (given by equation (3-8)) can be written as:

\[
P = \left[ \int_{\bar{\lambda}_1}^{\infty} \frac{\lambda^{(\alpha-\gamma)/(\sigma-1)}}{\rho^{1-\sigma}} M_p \mu(\lambda) d\lambda + n \int_{\bar{\lambda}_1}^{\infty} \frac{\tau^{1-\sigma} \lambda^{(\alpha-\gamma)/(\sigma-1)}}{\rho^{1-\sigma}} M_s \mu(\lambda) d\lambda \right]^{\gamma/(1-\sigma)}
\]

\[
= \frac{M_c^{1/(1-\sigma)}}{\rho} \left[ \frac{M_p}{M_c} \int_{\bar{\lambda}_1}^{\infty} \lambda^{(\alpha-\gamma)/(\sigma-1)} \mu(\lambda) d\lambda + n \frac{M_s}{M_c} \int_{\bar{\lambda}_1}^{\infty} \tau^{1-\sigma} \lambda^{(\alpha-\gamma)/(\sigma-1)} \mu(\lambda) d\lambda \right]^{1/(1-\sigma)}
\]

\[
= \frac{M_c^{1/(1-\sigma)}}{\rho} \left[ \frac{M_p}{M_c} \lambda^{(\alpha-\gamma)/(\sigma-1)} + n \frac{M_s}{M_c} \tau^{1-\sigma} \lambda^{(\alpha-\gamma)/(\sigma-1)} \right]^{1/(1-\sigma)}
\]

\[
= M_c^{1/(1-\sigma)} \lambda^{\gamma-\sigma}/\rho
\]

In open economy, aggregate revenue definition \( R = \int_0^{\infty} r(\lambda) M \mu(\lambda) d\lambda \) can be expressed as \( R = \int_{\bar{\lambda}_1}^{\infty} r_\gamma(\lambda) M_p \mu(\lambda) d\lambda + n \int_{\bar{\lambda}_1}^{\infty} r_s(\lambda) M_s \mu(\lambda) d\lambda \). Using (3-15) and (3-17), we have

\[
R = \int_{\bar{\lambda}_1}^{\infty} r_\gamma(\lambda) \lambda^{(\alpha-\gamma)/(\sigma-1)} M_p \mu(\lambda) d\lambda + n \int_{\bar{\lambda}_1}^{\infty} r_s(\lambda) \lambda^{(\alpha-\gamma)/(\sigma-1)} M_s \mu(\lambda) d\lambda
\]

\[
= M_c \frac{r_\gamma(\lambda)}{\lambda^{(\alpha-\gamma)/(\sigma-1)}} \left[ \frac{M_p}{M_c} \int_{\bar{\lambda}_1}^{\infty} \lambda^{(\alpha-\gamma)/(\sigma-1)} \mu(\lambda) d\lambda + n \frac{M_s}{M_c} \int_{\bar{\lambda}_1}^{\infty} \lambda^{(\alpha-\gamma)/(\sigma-1)} \mu(\lambda) d\lambda \right]
\]

\[
= M_c r_\gamma(\lambda)
\]

Aggregate quantity (3-2) can be expressed as

\[
Q = \left[ \int_{\bar{\lambda}_1}^{\infty} (P^{\sigma-1})^{\rho \sigma \lambda^{(\alpha-\gamma)/(\sigma-1)}} M_p \mu(\lambda) d\lambda + n \int_{\bar{\lambda}_1}^{\infty} (\tau^{1-\sigma} P^{\sigma-1})^{\rho \sigma \lambda^{(\alpha-\gamma)/(\sigma-1)}} M_s \mu(\lambda) d\lambda \right]^{\gamma/\rho}
\]

\[
= \left[ P^{(\sigma-1)} \rho \sigma \lambda^{(\alpha-\gamma)/(\sigma-1)} M_p \mu(\lambda) d\lambda + n \int_{\bar{\lambda}_1}^{\infty} \lambda^{(\alpha-\gamma)/(\sigma-1)} \mu(\lambda) d\lambda \right]^{\gamma/\rho}
\]

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\[
= \left[ M_c P^{(\sigma-1)^\rho} \rho^{\alpha \gamma} \tilde{\lambda}_c^{(\alpha-\gamma)(\sigma-1)} \right]^{1/\rho}
\]
\[
= M_c^{\sigma/(\sigma-1)} \rho^{\sigma} P^{(\sigma-1)} \tilde{\lambda}_c^{\sigma(\alpha-\gamma)}
\]
\[
= \rho M_c^{(\sigma-1)} \tilde{\lambda}_c^{\alpha-\gamma}
\]

Aggregate pollution is calculated as
\[
Z = \int_\infty^\infty \varepsilon L P^\sigma \lambda^a(\sigma-1)^{\gamma-\gamma} M_p \mu(\lambda) d\lambda + n \int_\infty^\infty \varepsilon L \tau^\sigma P^\sigma \lambda^a(\sigma-1)^{\gamma-\gamma} M_s \mu(\lambda) d\lambda
\]
\[
= \frac{\varepsilon \rho L}{\tilde{\lambda}_c^{(\alpha-\gamma)(\sigma-1)}} \left[ \frac{M_p}{M_c} \int_\infty^\infty \lambda^a(\sigma-1)^{\gamma-\gamma} \mu(\lambda) d\lambda + \frac{n}{\tau^\sigma} \int_\infty^\infty \lambda^a(\sigma-1)^{\gamma-\gamma} \mu(\lambda) d\lambda \right]
\]
\[
= \frac{\varepsilon \rho L}{M_c^{1/2}} \left[ \frac{M_p}{M_c} \int_\infty^\infty \lambda^a(\sigma-1)^{\gamma-\gamma} \mu(\lambda) d\lambda + \frac{n}{\tau^\sigma} \int_\infty^\infty \lambda^a(\sigma-1)^{\gamma-\gamma} \mu(\lambda) d\lambda \right]
\]

Proof of (3-42):
\[
\bar{r} = \tau^\sigma r_x(\tilde{\lambda}) + p_n r_x(\tilde{\lambda}_c)
\]
\[
= \tau^\sigma r_x(\tilde{\lambda}_c) \left( \frac{\tilde{\lambda}}{\tilde{\lambda}_c} \right)^{(a-\gamma)(\sigma-1)} + p_n r_x(\tilde{\lambda}_c) \left( \frac{\tilde{\lambda}}{\lambda_c} \right)^{(a-\gamma)(\sigma-1)}
\]
\[
= \tau^\sigma \sigma f_x \left( \frac{\tilde{\lambda}}{\lambda_c} \right)^{(a-\gamma)(\sigma-1)} + p_n \sigma f_x \left( \frac{\tilde{\lambda}}{\lambda_c} \right)^{(a-\gamma)(\sigma-1)}
\]
\[
= \sigma \left[ \tau^\sigma f_x \left( \frac{\tilde{\lambda}}{\lambda_c} \right)^{(a-\gamma)(\sigma-1)} + p_n f_x \left( \frac{\tilde{\lambda}}{\lambda_c} \right)^{(a-\gamma)(\sigma-1)} \right]
\]
\[
= \sigma \left[ \tau^\sigma f_x \left( \frac{\tilde{\lambda}}{\lambda_c} \right)^{(a-\gamma)(\sigma-1)} + p_n f_x \left( \frac{\tilde{\lambda}}{\lambda_c} \right)^{(a-\gamma)(\sigma-1)} - 1 \right] + p_n f_x
\]
\[
= \sigma (\bar{r} + p_n f_x)
\]
Proof of Proposition 3-2:

From the zero profit condition \( \pi_x(\lambda_x) = r_x(\lambda_x) / \sigma - f_x = 0 \), we have

\[
EL(P\rho)^{\sigma-1} \tau^{1-\sigma}(\sigma - 1) = \sigma f_x.
\]

Using \( P = M_c^{1/(1-\sigma)} \lambda_x^{-\alpha} / \rho \), we can get \( L\lambda_x^{(\sigma - 1)(\alpha - 1) - 1} = \sigma f_x M_c \lambda_x^{(\sigma - 1)(\alpha - 1) - 1} \).

Further, using the definition of \( \tilde{\lambda}_x \), we have

\[
\frac{L\lambda_x^{(\sigma - 1)(\alpha - 1)}}{\sigma f_x} = \tau^{\sigma-1} M_p \tilde{\lambda}_p^{(\sigma - 1)(\alpha - 1)} + n M_x \tilde{\lambda}_x^{(\sigma - 1)(\alpha - 1)}.
\]

Using the definitions of \( \tilde{\lambda}_p \), \( \tilde{\lambda}_x \) and the solution of \( M_p \), \( M_x \), we have the steady state equilibrium condition:

\[
\lambda_x^{(\sigma - 1)(\alpha - 1)} \sigma \left[ \delta f_x + \left[ 1 - G(\lambda_x) \right] n \right] = \tau^{\sigma-1} \int_\lambda^\infty \lambda^{\sigma-1} \left( \alpha \gamma - (\sigma - 1) \right) \lambda_x^{\sigma-1} \lambda^{\sigma-1} g(\lambda) d\lambda + n \int_{\lambda_x}^\infty \lambda^{\sigma-1} \lambda^{\alpha - 1} g(\lambda) d\lambda
\]

Total differentiating the steady state equilibrium condition with respect to \( \lambda \):

\[
\left[ \delta f_x + \left[ 1 - G(\lambda_x) \right] n \right] (\alpha - \gamma)(\sigma - 1) \lambda_x^{(\sigma - 1)(\alpha - 1) - 1} \frac{d\lambda_x}{d\lambda} = -\tau^{\sigma-1} \lambda^{(\sigma - 1)(\alpha - 1)} g(\lambda)
\]

Therefore,

\[
\frac{d\lambda_x}{d\lambda} = \frac{-\tau^{\sigma-1} \lambda^{(\sigma - 1)(\alpha - 1)} g(\lambda)}{\left[ \delta f_x + \left[ 1 - G(\lambda_x) \right] n \right] (\alpha - \gamma)(\sigma - 1) \lambda_x^{(\sigma - 1)(\alpha - 1) - 1}} < 0
\]

Total differentiating the steady state equilibrium condition with respect to \( \tau \):

\[
\frac{d\lambda_x}{d\tau} = \frac{(\sigma - 1)\tau^{\sigma-2} \int_\lambda^\infty \lambda^{\sigma-1} \lambda^{\alpha - 1} g(\lambda) d\lambda}{\left[ \delta f_x + \left[ 1 - G(\lambda_x) \right] n \right] (\alpha - \gamma)(\sigma - 1) \lambda_x^{(\sigma - 1)(\alpha - 1) - 1}} > 0
\]

Total differentiating the steady state equilibrium condition with respect to \( f_x \):
\[
\frac{d\lambda}{df_x} = \frac{\delta f_x \lambda}{\delta f_x f_x + n\left[1 - G(\lambda_x)\right] f_x^2} > 0
\]

Total differentiating the steady state equilibrium condition with respect to \(n\):

\[
\frac{d\lambda}{dn} = \frac{\left[1 - G(\lambda_x)\right]\left[\lambda_x^{(a-\gamma)(\sigma-1)} - \lambda_x^{(a-\gamma)(\sigma-1)}\right]}{\delta f_x f_x + n\left[1 - G(\lambda_x)\right] n (\alpha - \gamma)(\sigma - 1) \lambda_x^{(a-\gamma)(\sigma-1)-1}} > 0
\]

**Proof of Proposition 3-3:**

Aggregate consumption is given by (3-34): \(Q = \rho M_c^{1/(\sigma-1)} \tilde{\lambda}_c^{a-\gamma}\).

From (3-15), we have \(r_a(\tilde{\lambda}_c) = \left(\tilde{\lambda}_c^\gamma\right)^{(a-\gamma)(\sigma-1)} = \frac{L}{M_c \sigma f_x}\), so \(\tilde{\lambda}_c^{(a-\gamma)(\sigma-1)} = \frac{L\lambda_x^{(a-\gamma)(\sigma-1)}}{M_c \sigma f_x}\).

Then, we can get \(\tilde{\lambda}_c^{a-\gamma} = \left(\frac{L}{M_c \sigma f_x}\right)^{1/(\sigma-1)} \frac{\lambda_x^{a-\gamma}}{\tau}\). Aggregate consumption becomes:

\[
Q = \left(\frac{L}{\sigma f_x}\right)^{1/(\sigma-1)} \frac{\rho\lambda_c^{a-\gamma}}{\tau}.
\]

Differentiating aggregate consumption with respect to \(\lambda\) yields:

\[
\frac{dQ}{d\lambda} = \left(\frac{L}{\sigma f_x}\right)^{1/(\sigma-1)} \frac{\rho (\alpha - \gamma) \lambda_c^{a-\gamma-1} d\lambda}{\tau} < 0
\]

Differentiating aggregate consumption with respect to \(n\) yields:

\[
\frac{dQ}{dn} = \left(\frac{L}{\sigma f_x}\right)^{1/(\sigma-1)} \frac{\rho (\alpha - \gamma) \lambda_c^{a-\gamma-1} d\lambda}{\tau} > 0
\]

Differentiating aggregate consumption with respect to \(\tau\) yields:

\[
\frac{dQ}{d\tau} = \frac{\rho \lambda_c^{a-\gamma}}{\tau^2} \left(\frac{L}{\sigma f_x}\right)^{1/(\sigma-1)} \left[ (\alpha - \gamma) \frac{d\lambda}{d\tau} \frac{\tau}{\lambda_x} - 1 \right]
\]
where \((\alpha-\gamma)\frac{d\lambda_x}{d\tau} = \frac{\tau^{\sigma-1}\int_{\tau}^{\infty} \lambda^{(\alpha-\gamma)(\sigma-1)} g(\lambda)d\lambda}{\delta f_x + [1-G(\lambda_x)]n} \lambda^{(\alpha-\gamma)(\sigma-1)}\).

Using the steady-state equilibrium condition, this expression becomes

\[
(\alpha-\gamma)\frac{d\lambda_x}{d\tau} = \frac{\tau^{\sigma-1}\int_{\tau}^{\infty} \lambda^{(\alpha-\gamma)(\sigma-1)} g(\lambda)d\lambda}{\tau^{\sigma-1}\int_{\tau}^{\infty} \lambda^{(\alpha-\gamma)(\sigma-1)} g(\lambda)d\lambda + n\int_{\tau}^{\infty} \lambda^{(\alpha-\gamma)(\sigma-1)} g(\lambda)d\lambda} \]

\[
= \frac{1}{1 + \frac{n}{\tau^{\sigma-1}} \int_{\tau}^{\infty} \lambda^{(\alpha-\gamma)(\sigma-1)} g(\lambda)d\lambda \int_{\tau}^{\infty} \lambda^{(\alpha-\gamma)(\sigma-1)} g(\lambda)d\lambda} < 1
\]

Therefore, \(\frac{dQ}{d\tau} < 0\).

Differentiating aggregate consumption with respect to \(f_x\) yields:

\[
\frac{dQ}{df_x} = \frac{1}{\tau^{(\sigma-1)} \left( \frac{L}{\sigma} \right)^{(\sigma-1)} f_x^{1/(\sigma-1)-1} \lambda^{\alpha-\gamma}_x \left[ (\alpha-\gamma)(\sigma-1) \frac{d\lambda_x}{df_x} f_x \lambda_x - 1 \right]}
\]

where \((\alpha-\gamma)(\sigma-1) \frac{d\lambda_x}{df_x} f_x \lambda_x = \frac{\delta f_x}{\delta f_x + n[1-G(\lambda_x)]f_x} < 1\).

Therefore, \(\frac{dQ}{df_x} < 0\).
Figure 3-1. Effect of an increase in the environmental standard $\overline{\lambda}$
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Ting Levy was born in 1981 in China. She graduated from Xiangfan High School in Xiangfan, Hubei Province, China in 1998. She received her Bachelor of Science in economics in June 2002 from Huazhong University of Science and Technology, Wuhan, Hubei, China. In 2003, she began her graduate studies at Carleton University, Ottawa, Ontario, Canada and received her master's degree in economics in August 2005. She then moved to Gainesville, Florida and began her doctoral studies at the University of Florida. She specializes in international trade, environmental economics, economic growth and development. She received her Ph.D. in economics from the University of Florida in the fall of 2010. She currently resides in Boca Raton, Florida with her husband Eric Levy and 16 month old son Joshua.